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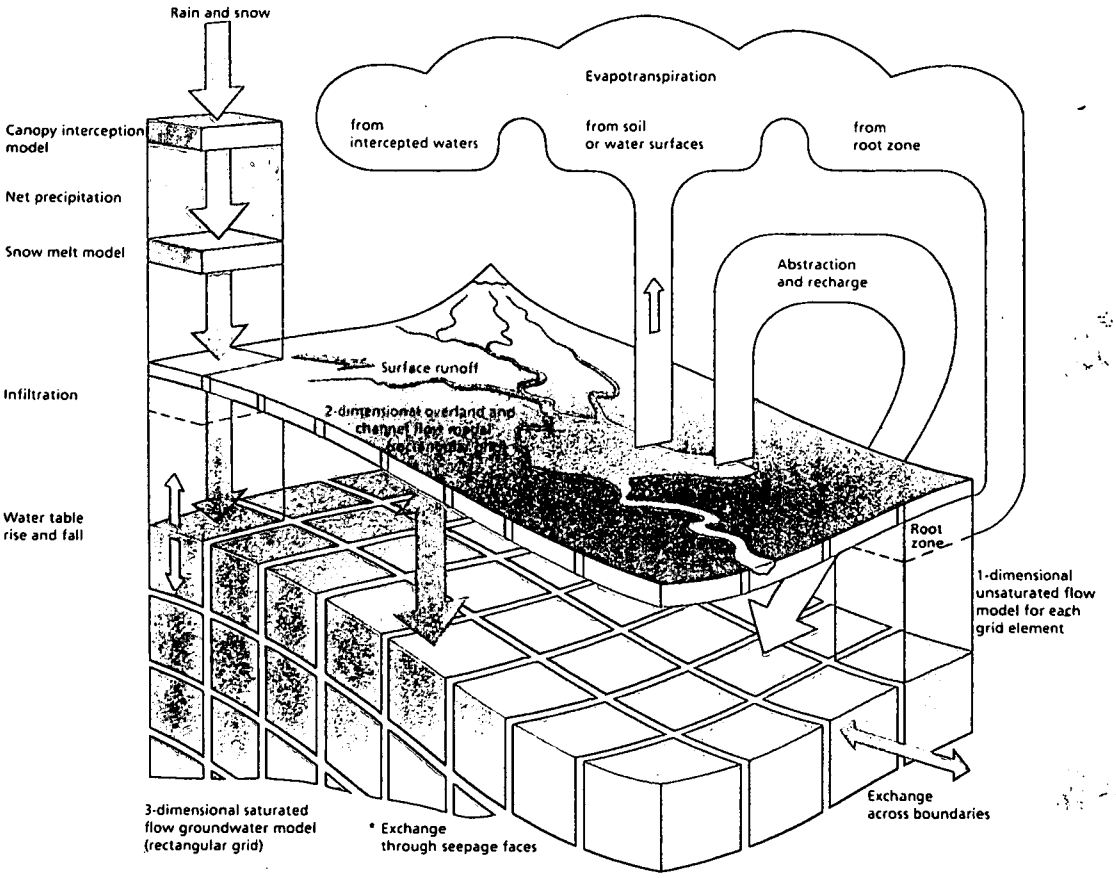

MIKE SHE

Water Movement Module

User Guide and Technical Reference Manual

MIKE SHE

Water Movement v. 5.3

User Guide and Technical Reference Manual

Edition 1.1

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PART I

User Guide

1 About this Manual

1.1 Purpose

The main purpose of this manual is to enable you to apply MIKE SHE for your hydrological problems in the best possible way. You should however be aware that you will not become a specialist by reading this manual and that you have to practice.

The Manual contains 3 parts. *Part I* is the *User Guide*, *Part II* contains the *Technical Reference Manual* and *Part III* includes *Appendices*. The structure and content of these 3 parts are briefly described below.

Part I – User Guide

Chapter 1, which you are reading now, gives a general background for reading the rest of this manual.

The *User Guide* describes in Chapter 2 how data files and directories should be organised as well as some basic notation used by the menu system.

Chapter 3 gives a very short description of which data you have to collect before you can run certain components of the modelling system.

A guide through all the specification menus for setting up the model is given in Chapter 4.

In Chapters 5 and 6 the procedure for running MIKE SHE and presenting the simulation results is described.

Part II – Technical Reference

The *WM Reference Manual* may be required when undertaking hydrological model applications with MIKE SHE WM. It provides a description of the theoretical background, solution techniques etc. for each component included in the WM module.

The manual contains 6 chapters describing each of MIKE SHE's basic flow modules.

Part III – Appendices

Appendix A contains a list of references.

Appendix B contains a number of examples which can be used by the User for getting started.

Appendix C contains documentation of MIKE SHE's Macropore Flow Module.

MIKE SHE is a dynamic software system which continuously undergoes a development process. New features are added and new process description modules emerge. Sometimes new modules are released even before they are included in the MIKE SHE user interface. Those modules are then activated by environment variables and typically additional input data and parameters must be specified in external ASCII files. This procedure ensures that new modules and features become available as soon as possible, after they have been developed and tested. Such new features are documented in separate Appendices. At present the following new modules exist:

Advanced module for simulation of preferential flow in the Unsaturated Zone (Appendix C).

1.2 Assumed User Background

Natural hydrologic systems as well as the hydrologic problems to be studies with the MIKE SHE are often very complex. In all application studies you need to construct a conceptual "model" of the area under study and try to fit this into a framework which is available in the MIKE SHE. This manual is not intended cover all aspects and problems arising during the modelling work, it is therefore important that a short training program is conducted in connection with a MIKE SHE transfer.

To apply MIKE SHE, requires a good understanding of mathematical modelling and hydrological processes in order to recognise the weaknesses and strengths in connection with using distributed and mechanistic models. Applying the MIKE SHE may in some cases seem time consuming. However, the MIKE SHE offers the possibility of analysing a number of hydrological problems which you are prevented from doing with other models.

The MIKE SHE software package has frequently been modified during the past years, and although efforts have been made to ensure codes free of errors, you may come across some as you go along. You should therefore always check all results carefully and certify that they are reasonable.

1.3 Other Manuals for MIKE SHE

The present manual covers hydrological applications of the MIKE SHE WM module simulating the within Water Movement in the different parts of the hydrological cycle i.e. unsaturated zone flow, overland and channel flow and groundwater flow.

MIKE SHE can accommodate a wider range of applications, which require add-on modules. At present User Guides are available for the following modules:

MIKE SHE AD Advection-Dispersion of solutes. This manual also describes MIKE SHE PT (Particle Tracking Module) and MIKE SHE SD (Sorption Degradation Module).
MIKE SHE PP Pre- and Postprocessing of input data and results.

2 Getting Started

2.1 Notations

MIKE SHE WM has been designed with a modular programme structure comprising six process-oriented components, each describing a major flow process of the hydrological cycle. Used in combination they describe the entire hydrological cycle. In this manual you will often find the following abbreviations for the components:

ET - Interception/evapotranspiration

OC - Overland- and Channel Flow

UZ - Unsaturated Zone

SZ - Saturated Zone

SM - Snow Melt

EX - Exchange between Aquifer and Rivers

Beside the process-oriented components MIKE SHE WM includes a Frame component (FR) which coordinates the parallel running of the process components by selecting their different time scales and organising their data interchanges.

A description of the theoretical background of different parts of MIKE SHE WM is given in the MIKE SHE WM Technical Reference Manual.

Individual components can be operated separately in MIKE SHE WM to describe individual processes. This may be relevant in a range of applications, where only rough estimates of data exchange from other parts of the hydrological cycle are required. An example could be a groundwater study where only approximate recharge estimates may be required and a full coupling to the unsaturated zone above the groundwater table is unimportant.

2.2 General Description of the Menu System

MIKE SHE was originally developed for UNIX platforms, but in 1996 the first PC release became available. The PC version of MIKE SHE runs on PENTIUM computers under Windows'95 or Windows NT.

The graphical user interface is based on a generalised graphical user interface developed by DHI. The UNIX version uses the industry standards XWindows and Motif as the basic software packages. The PC version uses eXceed as X-server.

Some facilities are general in most of the menus in the user interface i.e. item selection, help facilities, file selection facilities, load and save facilities, close facilities etc. which are shown in the figure below. A detailed description of the user interface is given in the MIKE SHE PP Manual.

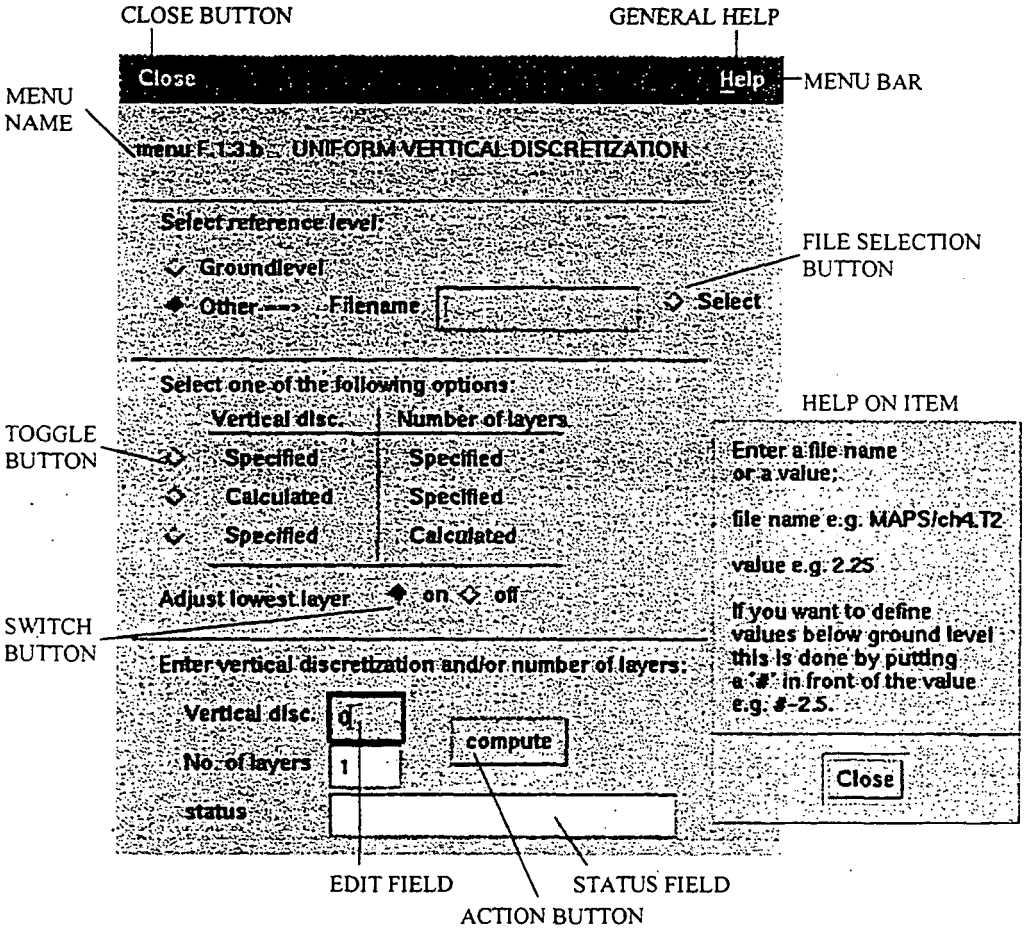

Figure 2.1 General facilities and expressions.

2.3 The File and Directory System

This section describes one possible way of organising data files for the WM- and PP modules. The structure described below is used at DHI and is convenient when several persons are using MIKE SHE in various projects on the same computer.

Often, several application studies are carried out simultaneously under one project and the MIKE SHE has been structured accordingly i.e. a much more flexible way of defining input data files is introduced by this generation of MIKE SHE. New conventions for data file names are also introduced below.

The home directory for a given modelling application could be

/DISK/she/data/Projid/Catchid

where Projid identifies the project and Catchid indicates for example the name of the catchment you are about to develop a model for.

The input data file for a simulation with the WM module is called the flow input file - fif. It is read directly by the MIKE SHE and should be located on the home directory. The execution of the MIKE SHE should also be made from here and usually, the pre- and postprocessing programs should also be executed from here. A new fif is created for each new application or calibration run.

The fif is a binary file which cannot be edited by a normal text editor. It is created by the setup program. The input file for this program is called the file selection file - fsf. The fif and the fsf are in principle the only data files you should keep on the home directory. The two data files have the same prefix (e.g. test1) - the simulation identification name.

Under the Catchid home directory seven sub-directories should be created:

MAPS, DIGFILES, TIME, DBASE, PLOT, MACRO,
SIGNALS

The MAPS directory contains usually all the input data files of the spatially distributed data and data codes (e.g. vegetation distribution), which are retrieved and inserted in the fsf data file by the setup program. Also measured data used for calibration (e.g. maps of potential heads) are stored here.

The TIME directory should contain all the input data files of time series (e.g. precipitation), which are read during a simulation run. Also calibration series (e.g. river discharge) are stored here.

The DBASE directory contains different data bases with default parameters for some of the variables especially for calculations with the UZ component of MIKE SHE.

The DIGFILES directory contains usually digitised data of any kind.

The PLOT directory contains the specification files for different plots which are produced in the application.

The MACRO directory contains other specification files for the utility programs. The different utility programs search for data file names with different suffix - see later.

The SIGNALS directory contains message files from execution of MIKE SHE WM.

Results from a simulation run with MIKE SHE are stored in two output data files, both with the simulation identification name as prefix and the suffix 'fpf' and 'frf'. They are stored at a result file directory - $sheres - defined in your login environment file.

A detailed description of the directories and data files are given in the PP manual.

3 Modelling Procedure - Step by Step

3.1 Defining the Hydrological Model

MIKE SHE is applicable to a wide range of problems occurring in the hydrological cycle thus you have to limit the problem before you start to setup the model. In fact you should already have thought about this before you initiated the collection of data! At least you have to consider the following issues:

*What are the important hydrological phenomena to be studied. Is it a groundwater management problem which requires a description of the entire hydrological cycle or can it be confined to a few parts of the hydrological cycle.

*What is the spatial scale of the problem? Is it a study of overland and channel flow where it is important to include the entire topographical catchment in the model or is it only necessary to include a small area which is a hydrological unit concerning subsurface flow.

*What is the temporal scale of the problem ? Is it a study which only concerns overland and channel flow with no interaction with the groundwater and therefore with limited "memory" or is it a study of a subsurface flow system which "remembers" what happened decades ago.

*Which components should be included ? After having defined the dominating hydrological phenomena of the problem you can define which MIKE SHE modules that are necessary to solve the problem. In the MIKE SHE WM short description is given an overview of possible types of applications with the different components.

*Which add-on modules should be run and what implications does this have on the choice of components to be included; check with the manuals for the add-on module what components are required to simulate the problem under consideration.

3.2 Collecting Data

The application of distributed models which describe the physics requires the provision of large amounts of parametric and input data. Some of these may even be time-

dependent. Collecting data and parameters may be more or less time-consuming dependent on several different factors:

- which modules are included in your simulation;
- which temporal and spatial scales are to be considered;
- data availability and what data should be collected by initiating a monitoring program;

It is important to emphasise that MIKE SHE allows the user to utilise a large quantity of data, but it does not necessarily restrict the use of MIKE SHE if all data are not available. A model that is set up, or "instantiated", using MIKE SHE can be simplified according to its users conceptualisation of the natural system and the data availability.

A list of data and parameter requirements for the different modules is given on the next pages:

Data and parameter requirements for each grid square or channel link

Frame

Input data	Horizontal discretisation Ground surface elevation Distribution codes for rainfall and meteorological stations

Interception

Model parameters (Rutter Model) (for each crop type)	Canopy drainage parameters Canopy storage capacity (time varying) Ground cover indices (time varying)
Model parameters (K-J model) (for each crop type)	Leaf area index (time varying) Interception capacity coefficient
Input data	Rainfall rate

Evapotranspiration

Model parameters (P-M equation)	Canopy resistance Aerodynamic resistance Ground cover indices (time varying) Ratio between actual and potential evapotranspiration as a function of soil moisture tension Root distribution with depth
Model parameters (K-J model) (for each crop type)	Empirical constants describing the ration between actual and potential evapotranspiration as function of soil moisture Leaf area index (time varying) Rooting depth (time varying) Root distribution coefficient
Input data	Meteorological data

Overland and channel flow

Model parameters	Strickler roughness coefficients for overland and river flows Detention storage capacity on ground surface
Input data	Specified levels and flows at boundaries Man-controlled discharges Topography of overland flow plane and river cross sections Riverbed lining permeability (leakage coefficient)

Data and parameter requirements for each grid square or channel link

Unsaturated zone

Model parameters (for each soil type)	Soil moisture tension/content relationship Unsaturated hydraulic conductivity as a function of soil moisture content Maximum bypass ratio of net rainfall
Input data	Distribution codes for soil profiles Distribution codes for soil types in soil profiles Vertical node discretisation in UZ

Saturated zone

Model parameters	Storage coefficients Saturated hydraulic conductivities Drainage depth Time constant for drainage routing
Input data	Specified flows, gradients and heads at boundaries Location of abstraction or recharge wells Pumping and recharge rates Vertical node discretisation in SZ

Snow melt

Model parameters	Degree-day factor Snow zero plane displacement Snow roughness height
Input data	Meteorological and precipitation data

4 Building a MIKE SHE Model

Preparation of a model for a specific study is highly dependent on which components you have decided to include in your simulation.

As shown in menu F.1 (see Fig. 4.1) the specification of data files and parameters is done for each component. In the succeeding sections is given an explanation for setting up each component.

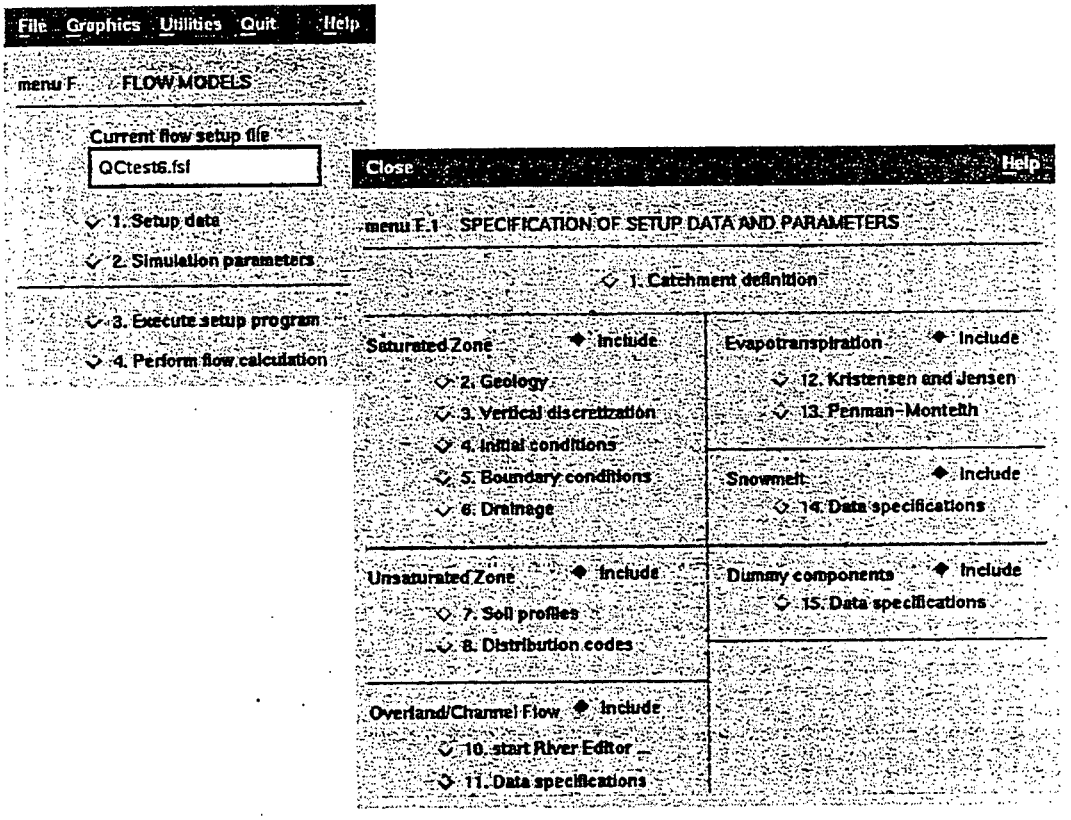

Figure 4.1 Preparation of a model.

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A major effort in setting up of a model is to process data i.e. digitise, interpolate etc. Please refer to the Pre- and Postprocessing Manual to get detailed explanation of the processing of data and the data formats for time series and matrix series.

4.1 Catchment Definition

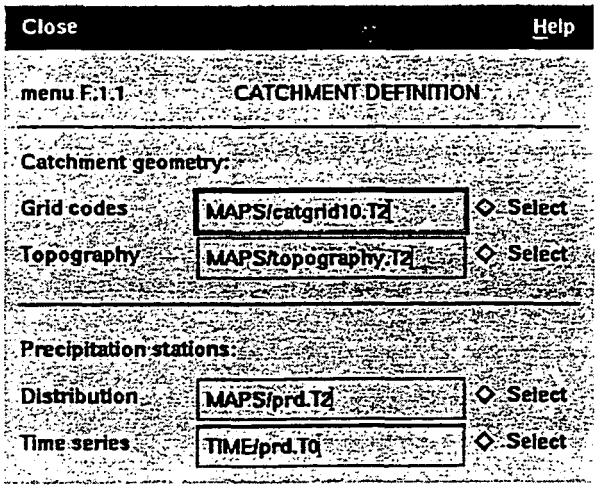

Figure 4.2 Catchment definition.

Catchment geometry

Independent of the components to be included in your model the first and necessary step is to define the model area and some main parameters describing the area. On catchment scale the model boundary could either be the topographic water divide, a ground water divide or a combination of the two, but in general there are no constrains on the definition of the model area. However, it is important to note that the boundary conditions should be appropriate both for the surface water and the subsurface water system.

The first thing to specify in menu F.1.1 is the catchment grid code data file. You can prepare this data file manually but the easiest way is to digitise your model area on a map and run the utility program MSHE.OL. MSHE.OL also allows you to automatically add boundary points along the boundary of the model area. The Pre- and Postprocessing Manual (Section 3.2) gives a detailed description of how to prepare your catchment grid code data file.

Topographical conditions which are used to determine flow directions for overland flow are specified either in a data file in which case you should enter the data file name or as a constant value (level).

Precipitation stations

Precipitation exerts usually large spatial variations. The distribution of the precipitation can be specified in a grid code data file. If data are available from more than one precipitation station you can for example define the areas associated with each station as Thiessen polygons either created manually with an editor or from digitised data with the MIKE SHE Overlay tool. The distribution is determined by codes (1.0, 2.0 etc.) which refers to the record number in the data file containing time series of precipitation from the different stations as illustrated in Fig. 4.3.

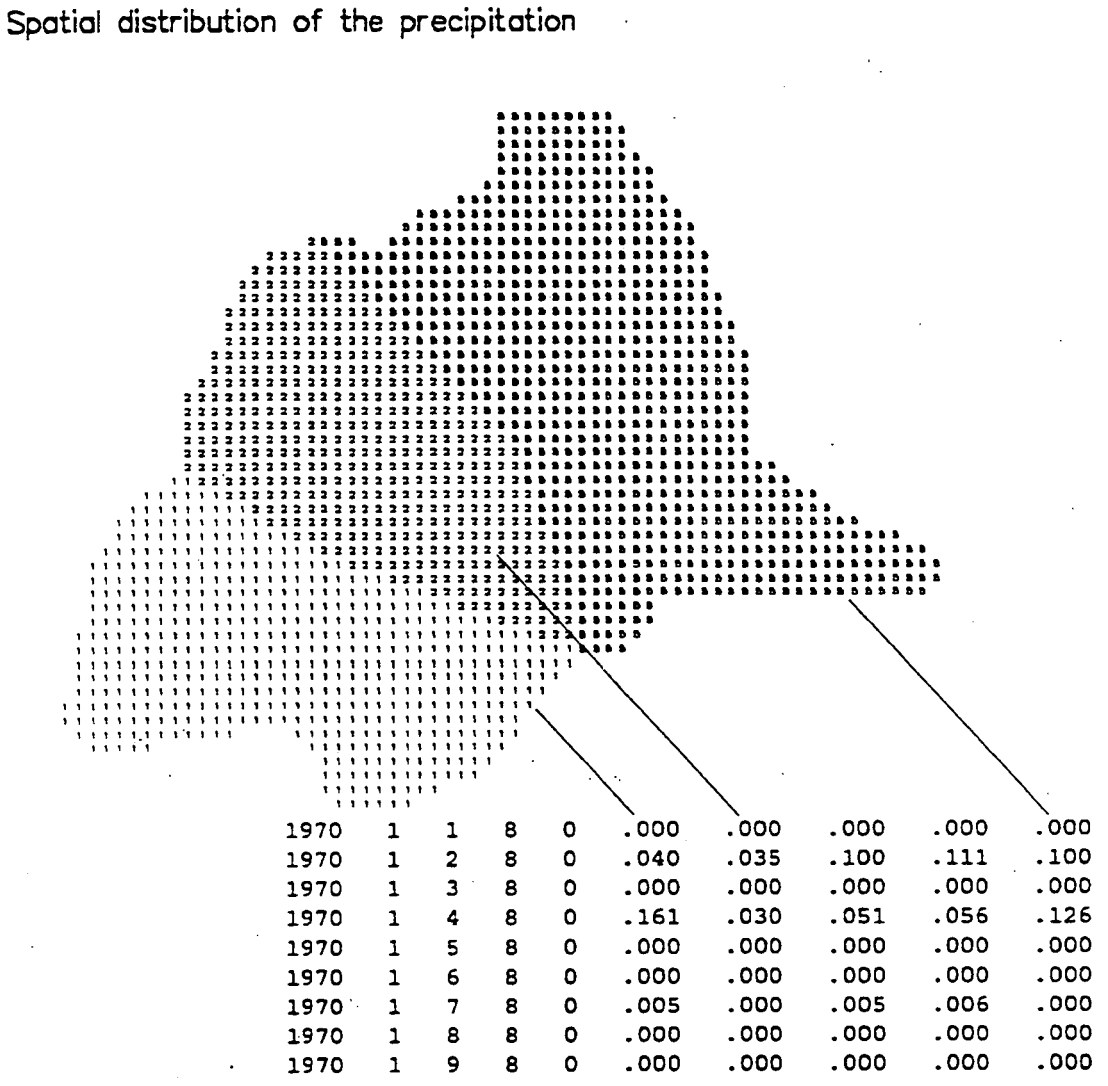

Figure 4.3 *Distribution of precipitation and its reference to the time series of precipitation.*

Uniform precipitation can be specified with a single value which refers to a particular record in the data file containing time series of precipitation. Finally a constant rainfall rate may be specified instead of a time-series file.

4.2 Overland and Channel Flow Component

The input data for the Overland and Channel flow component is given in the Menu F. 1.11 (see Fig. 4.4).

Overland Flow
For the Overland Flow part, three sets of parameters are required:

- o Initial water depth at the ground surface (ponded water)
- o Detention storage
- o Strickler roughness coefficients

All three sets of parameters can either be given as default values or as 2-D maps with a type two data file format. (T2-file).

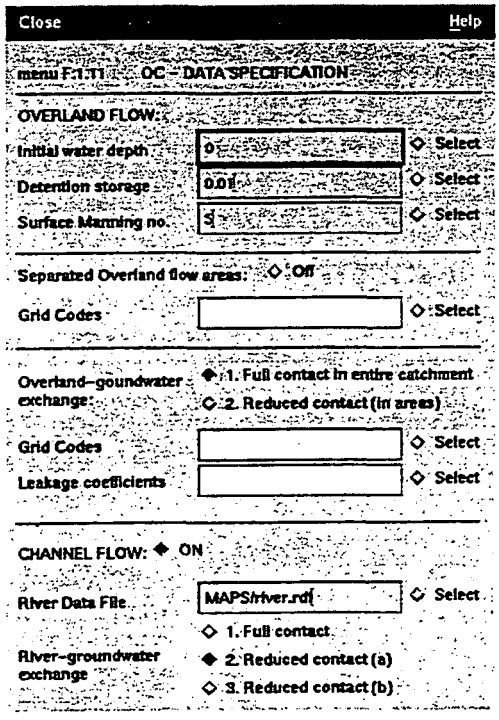

Figure 4.4 Input data for the Overland and Channel flow component

As from version 5.24 two additional optional features are included that enable specification of separated overland flow areas and reduced leakage calculation.

Separated Overland Flow Areas
Specification of separated overland flow areas enable simulation of areas which are separated by dikes or embankments. Separated overland flow areas are defined by specifying a T2 grid-code file which contains a code value for each flow area. The model will then disable overland flow between grids with different flow codes. Thus, embankments can be simulated by defining different flow codes on each side of the embankment.

Overland Ground Water Exchange

In situations where a soil profile becomes completely saturated MIKE SHE disables the unsaturated zone calculation. If, on the same time, there is ponded water on the ground surface the exchange of water between the overland flow component and the groundwater component is calculated based on the vertical hydraulic conductivity in the upper layer of the saturated zone and the hydraulic gradient between the surface water level and the ground water table in the upper layer of the saturated zone. Often the vertical hydraulic conductivity of the upper layer in the saturated zone is not representative for the permeability of the top soil (the top soil is usually described more detailed in the UZ model in MIKE SHE but the parameters is not used when UZ "dissapears"). In such situations a leakage coefficient can be specified. The exchange of water between the surface water and ground water is then calculated based on the specified leakage coefficient and the hydraulic head between surface water and ground water. This option is often useful under lakes or on floodplains which may be permanently or temporarily flooded, and where fine sediments may have accumulated creating a low permeable layer (lining). The value of the leakage coefficient may be found by model calibration, but a rough estimate can be made based on the saturated hydraulic conductivities of the unsaturated zone or in the low permeable sediment layer, if such data area available. If the reduced leakage option should be applied a grid file must be specified defining the grid points with reduced leakage (code value 2) and grid points where the normal (full contact) should be used (code value 1). For grid points with code value 2 a leakage coefficient must be specified, either as one uniform value or as distributed values specified in a T2 file.

Channel Flow

The preparation of the river network is carried out with the Graphical River Editor described in the PP manual.

The output file from the river editor should be specified in Menu F. 1.11. Three options for describing the river-aquifer exchange is available (ref. MIKE SHE Technical Ref. Manual):

- full contact i.e. the exchange flow is determined from the hydraulic parameters of the geological layers adjacent to the river;
- reduced contact i.e. the river lining thickness and hydraulic conductivity is taken into account when calculating the exchange flow. Reduced contact can be calculated in two different ways (a) and (b):

  a: the hydraulic exchange flow is calculated on the basis of the hydraulic conductivity of both the aquifer adjacent to the river AND the hydraulic conductivity and thickness of the river lining;

  b: the hydraulic exchange flow is calculated only on the basis of the hydraulic conductivity and thickness of the river lining.

4.3 Unsaturated Zone Component

The Unsaturated Zone component solves the 1-D Richards equation in a number of independent soil columns connecting the overland flow component and the groundwater component.

For solving Richards equation two important hydraulic functions are required for all soil types which characterise the individual soil profiles within the model area:

- o the soil moisture retention curve $\psi(\theta)$
- o the hydraulic conductivity function $K(\theta)$

This information is stored in a soil property database. The database menu is accessed from the main menu under item **D. Database**.

Soil Property Database

Fig. 4.5 shows the soil property database Menu D.1. The left hand part of this menu describes the soil properties for a specific soil type. All soil types stored in the database are shown on the left hand part of the menu.

If the soil type database is to be established for a new application it is possible to import soil types from existing databases (by using the Edit button (1)). The parameters for imported or existing soil types can be modified by selecting the concerned soil type on the right hand part (2). The corresponding parameter values will then appear in the left hand part of the menu. Also by using the data base tools you are able to make either a print of all parameters in the soil or a graphical presentation of the retention curve and the hydraulic conductivity function.

The following parameters need to be specified:

- o soil moisture at saturation (Theta_s)
- o soil moisture at effective saturation (Theta_eff)
- o capillary pressure at field capacity (pF_fc)
- o capillary pressure at wilting point (p_FW)
- o residual soil moisture content (Theta_res)
- o exponent in hydraulic conductivity function (Expo)
- o saturated hydraulic conductivity (K_s) [m/s]

pF is $\log_{10}(-100_\psi)$ where ψ is in unit [meter]. Notice that ψ is always negative under unsaturated conditions.

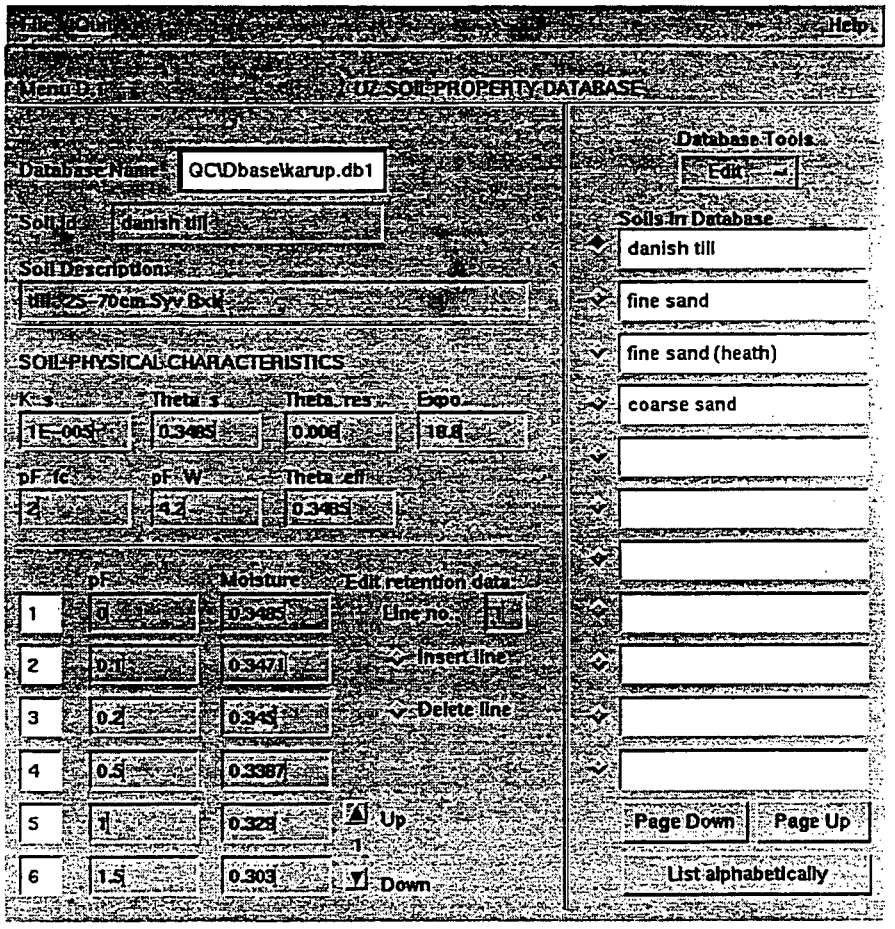

Figure 4.5 Soil Property Database.

The soil moisture at effective saturation Teta_eff is the air entry value at the soil moisture retention curve and the maximum achievable soil moisture content.

The exponent n in the hydraulic conductivity function is smaller for sandy soils compared to clayey soils.

The data points describing the soil moisture retention curve is given as a table of pF - Θ (moisture content) values. The table should be specified starting with the lowest value of pF (wettest condition) and given in increasing order of pF.

In order to get a smooth retention curve MIKE SHE adopt a cubic spline curve fitting procedure: As a minimum you should specify water content at saturation, field capacity and wilting point, respectively.

The table for the soil moisture retention curve can be edited directly by clicking the edit field, and points can be deleted or inserted by pressing the 'Insert line' or 'Delete line' toggles, respectively.

After the database has been constructed it can be saved by using the 'File' key from the menubar. This key should also be applied to load an existing database.

Once the soil property database is established including all soil types occurring in the model area, the input data for the UZ component should be specified from menu F.1.7 (Soil profile definition) and F.1.8 (Soil profile distribution).

The following information is required:

- o distribution of soils layers within each profile
- o vertical spatial resolution within each profile
- o horizontal distribution of soil profiles
- o horizontal distribution of bypass codes
- o bypass parameter for each bypass code
- o horizontal grid codes specifying paved areas (impermeable)
- o grid codes specifying in which grid squares uz calculations are carried out.

Soil Profile Definition

In menu F.1.7 (see Fig. 4.6) the distribution of soil layers (i.e. depth and thickness of each soil type) in the individual profiles can be specified as well as the vertical increments of the computational nodes in the numerical scheme.

The individual soil profiles are defined in the upper part of menu F.1.7. Each profile should be given a number and an identification (Profile id.). Each profile is defined by a sequence of soils. The base of each is specified in the 'Depth' edit field.

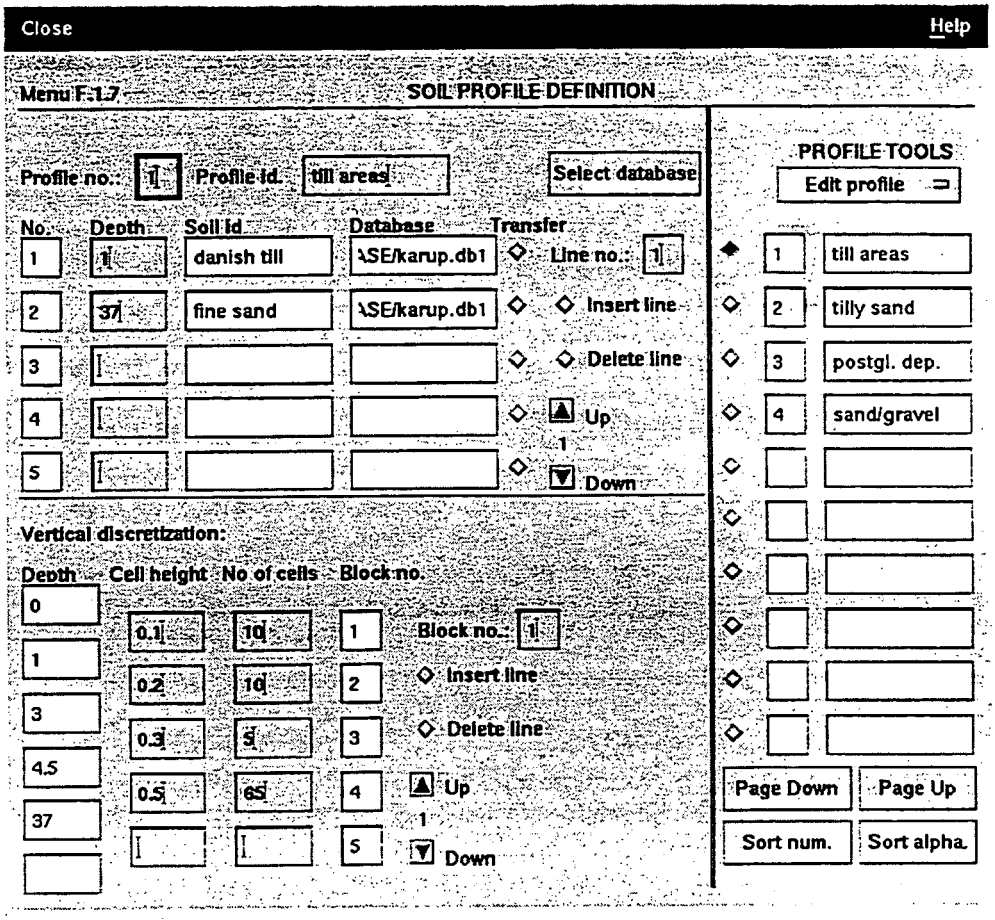

Figure 4.6 Soil profile definition.

The soil properties can be retrieved from one or more databases as illustrated in Fig. 4.6 and directly transferred into the profile. This is done by pressing 'Select database' and select from the pop-up menu which gives you a window with the names of the soils in the selected database. The soil is retrieved by clicking on the toggle to the left of the soil name on the 'database window' and afterwards click on the toggle to the right of the 'Database' edit field. The system allows you simultaneously to retrieve soils from different databases by opening more than one 'database window'.

The profile can be modified by inserting or deleting individual soils with the 'Insert line' and 'Delete line' facilities or by changing lower boundary of individual soils.

The vertical discretisation used in the computations is specified by two figures, the cell heights and the number of cells having this height. MIKE SHE allows variable discretisation in the individual profiles. The discretisation should be tailored to the profile description and the required accuracy of the simulation. If the full Richard's equation is used the vertical discretisation may vary from 1-5 cm in the uppermost grid points to 10-50 cm in the bottom of the profile. If the simplified version of Richard's equation is used (tension term ignored) a more coarse discretisation may be used. For instance 10-25 cm in the upper part of the soil profile to 50-100 in the lower part (see Section 1.5 and MIKE SHE Technical Reference Manual).

Notice that at the boundary between two blocks with different cell height the two adjacent boundary cells are adjusted to give a smooth change in cell heights.

Soil type distribution and vertical discretisation is specified for all soil profiles accounted for in the model area. Their horizontal distribution is given in menu F.1.8.

Distribution Codes

The spatial distribution of computational columns in which unsaturated zone flow is computed is defined in Menu F.1.8 as shown in Fig. 4.7. This menu is divided into two parts, the definition of computational columns (the left hand part) and specification of grid codes (the right hand part).

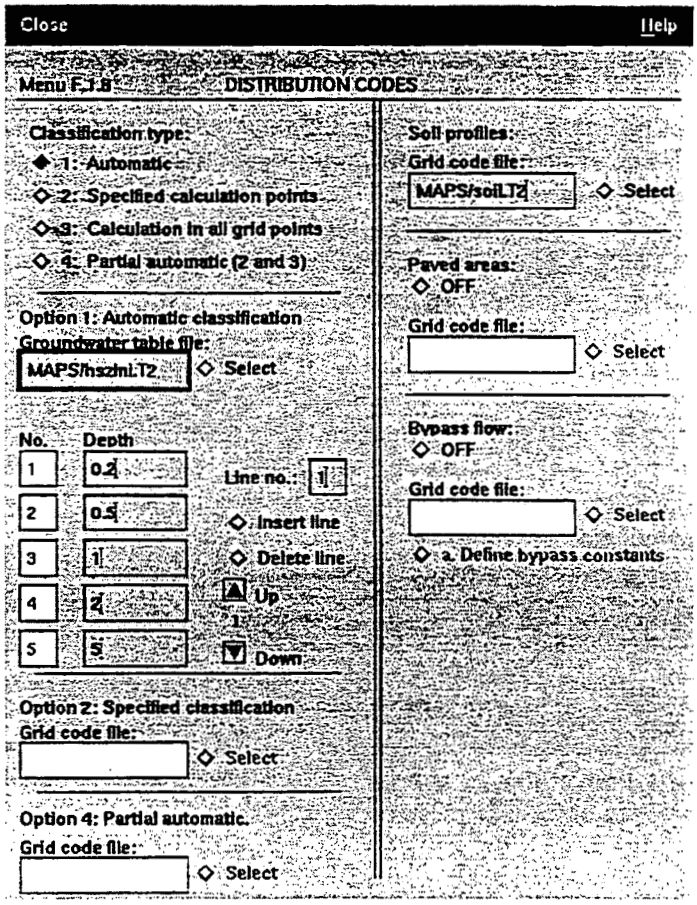

Figure 4.7 Distribution codes.

Classification Type

Since UZ computations in all grid squares for most large scale applications require too much computation time, MIKE SHE enables computations only for a representative subset of grid squares (see the MIKE SHE Technical Reference Manual). The subset classification is done automatically by the setup programme according to soil and vegetation types, climatic conditions, and depth to the water table.

If the 'Automatic' classification is chosen, a datafile containing the distribution of depths to the water table in the model area and a table with intervals of groundwater depths as a basis for the classification should be given. The number of computational columns depends on how narrow the intervals are specified.

Alternatively an existing datafile specifying grid squares where UZ computations are carried out can be specified - select 'Specified' as classification type and specify the grid code data file. Grid codes range from 2 to number of UZ columns. The location of the computational grid is specified by -code and simulation results is then transferred to all grids with the value +code. For instance if a grid code holds the value -2 an UZ computation will be carried out for the profile located in that grid. Simulation results will subsequently be transferred to all grid codes with code value 2. An easy way to generate a T2 file to be used for specification of UZ computational columns is to use let the MIKE SHE setup program generate an automatic classification first, and subsequently extract

UZ classification grid codes using the MSHE_IR utility program. The output T2 file can be edited in the 2D editor as desired and used to specify UZ computational grids.

For small scale detailed studies the user can specify that computations are carried out in all soil columns - select 'All' as classification type.

Finally a combination of Automatic classification and specified classification is available. If this option is chosen a T2 grid code filename must be given. In areas where specified computational grids should be used the grid codes must be specified as described above (under specified). In grid points where automatic classification should be used the grid code 1 must be given.

The following T2 grid code files are required for the UZ component:

- soil profile distribution over the model area
- paved (impermeable surface) areas
- distribution of bypass flow conditions (should often be dependent on the soil profile distribution)

Soil Profiles
The grid codes describing the horizontal distribution of soil profiles should correspond to the numbers of the individual soil profiles in Menu F.1.7. A grid code map can be constructed from digitised information of soil maps. If the model area is homogeneous a single code value may be specified.

Paved Areas
Paved areas are defined by the code 2 (two) in a grid code data file. Other areas are given the code 1 (one).

Bypass Flow
If any soil profiles includes bypass flow (ref. MIKE SHE Technical Reference Manual) the bypass option should be ON. A grid code map defines the distribution of the bypass conditions. For each code the bypass parameters are specified in Menu F.1.8a. The parameters are:

- byp is the maximum bypass ratio of the net rainfall which can occur,

- thr1 is the threshold water content at 10 cm and 50 cm below which the bypass ratio is reduced compared to 'byp'

thr2 is the minimum water content at 10 cm and 50 cm at which bypass occurs (see the Technical Reference Manual).

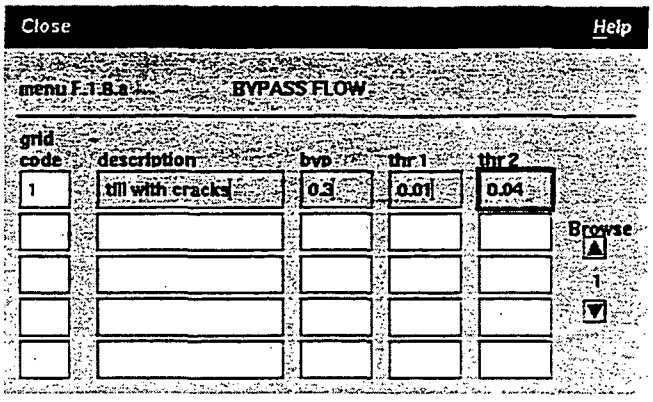

Figure 4.8 Bypass flow.

A more advanced macropore flow module is also available for MIKE SHE (cf. Appendix C).

4.4 Saturated Zone Component

Setting up the saturated zone component requires five major steps:

- o definition of the geological model
- o definition of the vertical numerical discretisation
- o definition of the initial conditions
- o definition of the boundary conditions
- o definition of the degree of drainage

The geological model is in principle defined independently from the rest of the model setup. This provides a great flexibility in the development of the saturated zone model, thus the same geological model can be applied for different vertical discretisation and in principle also for different modelling areas.

Geological model

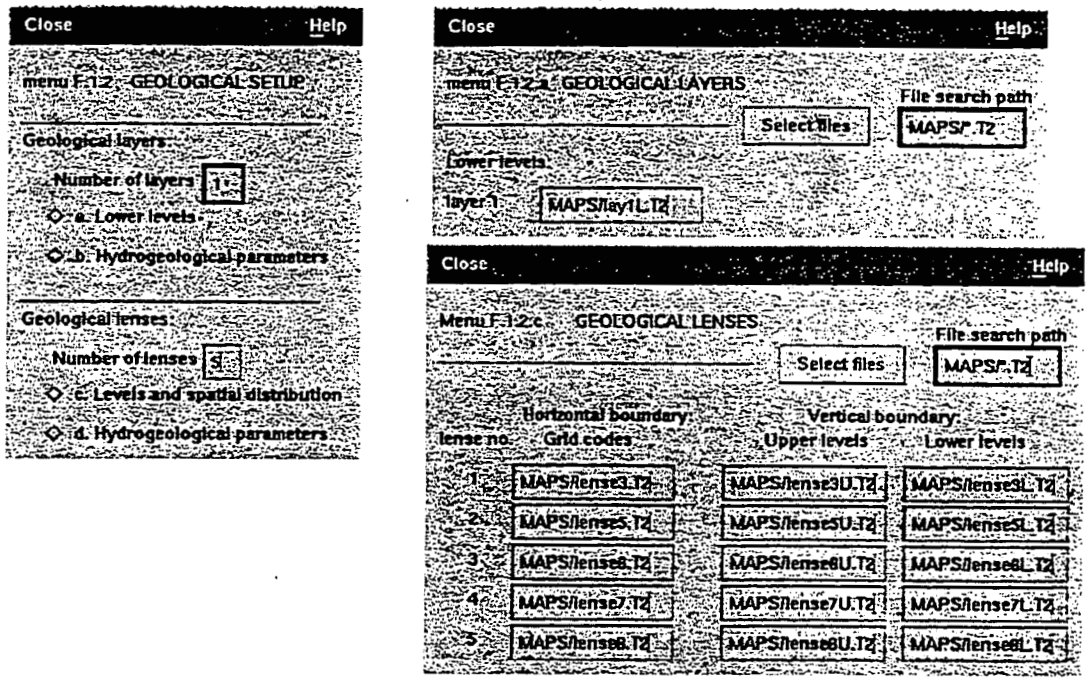

Figure 4.9 Geological model.

Establishment of the numerical representation of the geological model is maybe the part that requires most pre-processing work. Before you enter this part of the model development a digitised interpreted geological model should be available.

The interpreted geological model should describe a number of geological formations which in the MIKE SHE terminology consists of layers (formations which cover the entire area under consideration) and lenses (formations which only partly cover the area under consideration).

The digitised and processed geological model includes a number of data files with information of lower base of each of the geological layers, upper and lower boundaries of each of the geological lenses combined with a grid code data file defining its horizontal extent. Furthermore, estimates of the hydraulic parameters and eventually their distribution in the area under consideration for each of the geological formations should be determined.

Once this information is available the setup procedure is straight forward; go through each of the items in menu F.1.2 and specify relevant data file names or parameter values.

Notice that parameters for one layer more than specified in your geological model are required; this is most often the so-called "impermeable bed" which in MIKE SHE in some cases could be part of the modelling area. You should here specify small values for both horizontal and vertical hydraulic conductivities.

Vertical discretisation

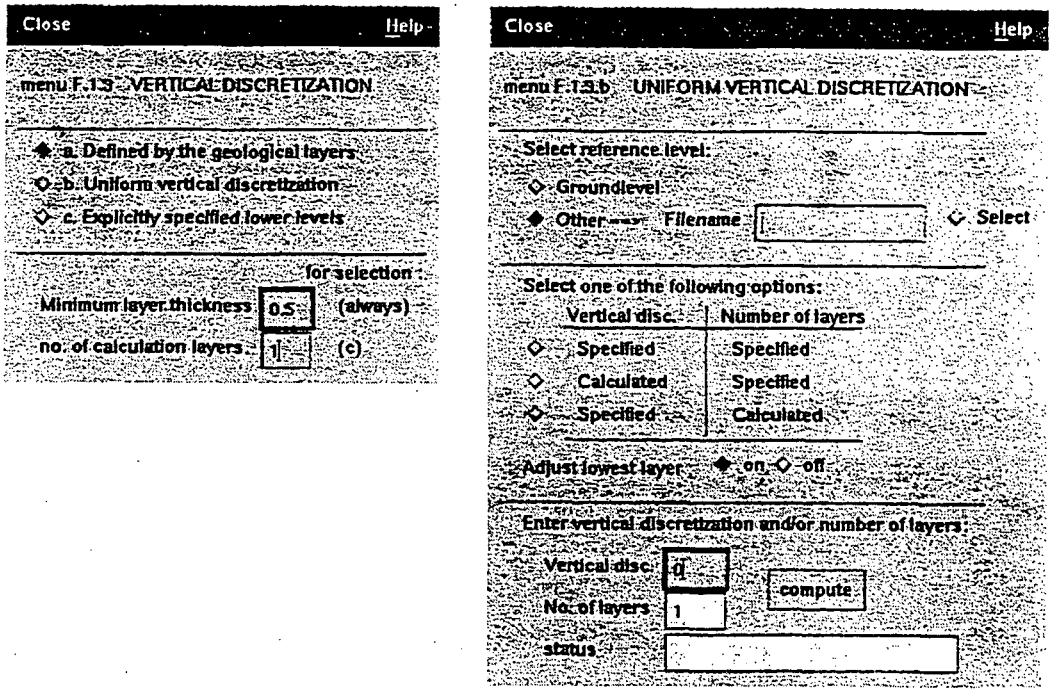

Figure 4.10 Selection of vertical discretisation.

The vertical discretisation in the saturated zone model can be defined in three ways; by the geological layers in which case there will be one calculation node in each geological layer, by a constant thickness of each calculation layer which is valid through the model area or by explicitly defining the lower level of each calculation layer. In the first and last case the minimum thickness of the calculation layers has to be specified in order to adjust the geological model or the specified levels to this value. In the last case you should also specify the number of computational layers in your model.

Vertical discretisation defined by the geological layers

Groundwater flow in a multi-layer aquifer can be described by a model in which the computational layers follow the interpreted geological layers, see Fig. 4.11. Each layer is characterised only by its base level specified either by a constant default level or by a map as in a type two data file. For each layer you should define the hydrogeological parameters (horizontal and vertical hydraulic conductivity, storage coefficient and specific yield) which all can be specified as uniform values or as spatially varying parameters in a type two data file.

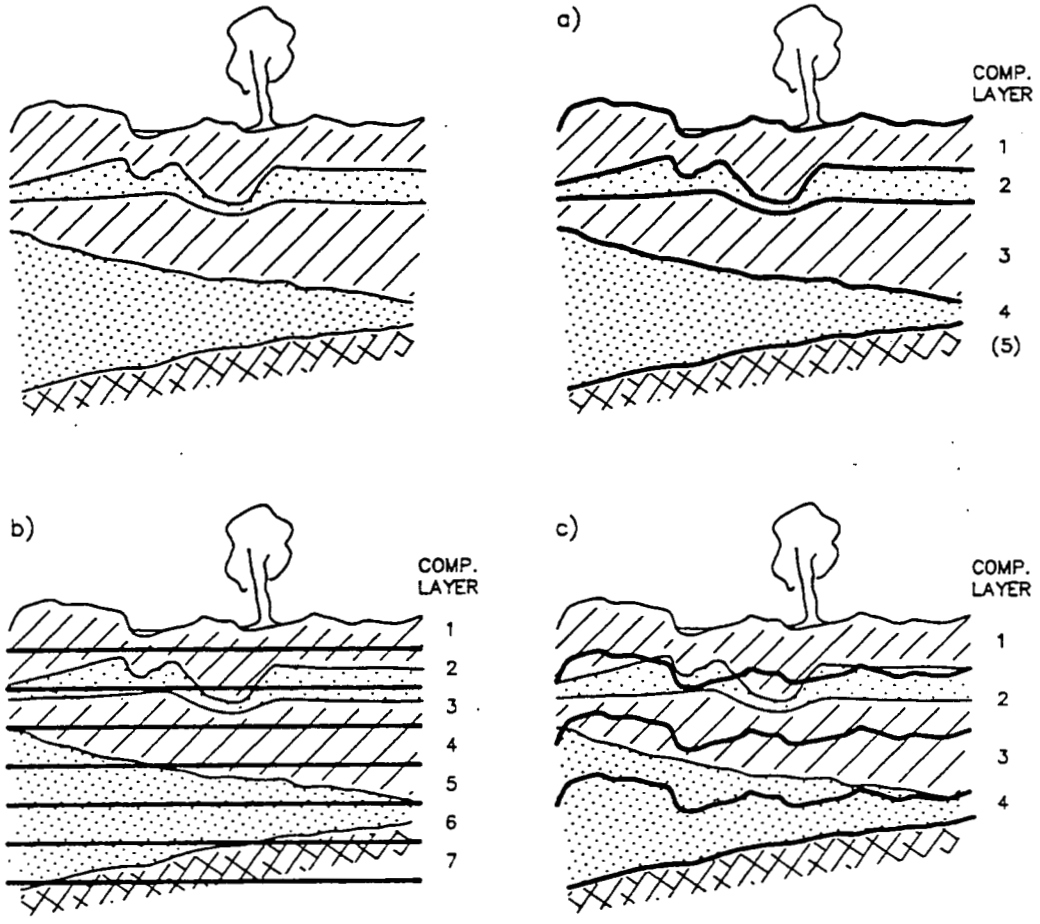

Figure 4.11 *Different representation of an aquifer with vertical geological variability.*
a: geological layers equal to computational layers
b: uniform vertical discretisation
c: b + adjustment of bottom to reference level

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Vertical discretisation with constant thickness

Computational layers of constant thickness are mostly used for problems where you afterwards want to simulate solute transport with the Advection-Dispersion Module.

Defining a constant thickness of each computational layer provides you with three further options; you can specify both the thickness and the number of calculation layers or you can specify either the number of calculation layers or the thickness of your layers and let the model compute the remainder, see menu F.1.3.b.

Furthermore, the possibilities to define a model with constant thickness of the computational layers "inside" the model and spatial varying thickness of the top layer and/or the bottom layer. The top layer thickness is determined by the selection of a reference level i.e. if you chose a reference level different from the ground surface (e.g. a groundwater table) it will be adjusted according to the reference level. The bottom layer thickness can be adjusted to reach the "impermeable bed" defined by the geological model by pressing the "on" toggle.

When you have selected your choices press "compute" to let the model determine the final vertical discretisation.

Explicitly defined vertical discretisation

If you select to define the vertical discretisation explicitly you can combine the possibilities described above. Each computational layer is then defined by its lower base.

Initial conditions

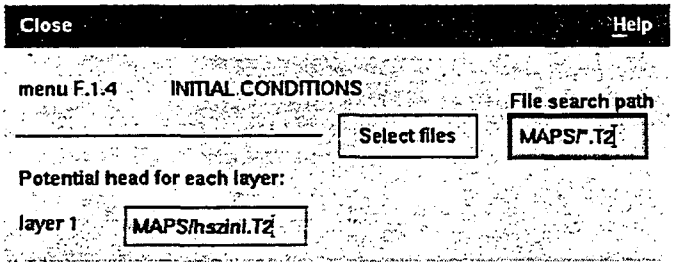


Figure 4.12 Initial conditions.

The initial conditions for the saturated zone component specified as a potential head level for each distribution computational layer. This level can be specified in three different ways, i.e. a constant default level, as a constant level with reference to the topographical surface given by a single value with a # in front of it or as distributed values by specifying a data file name with distributed the data.

Boundary conditions

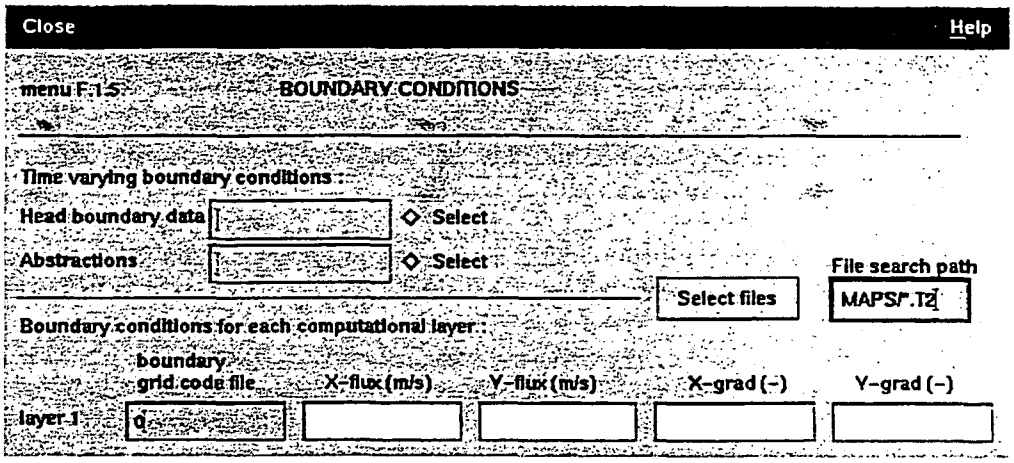


Figure 4.13 Boundary conditions.

Boundary conditions for each layer in the saturated zone component can be specified in a number of different ways.

The upper boundary of the top layer is always either the infiltration/exfiltration calculated by the unsaturated zone component or a specified fraction of the precipitation if the unsaturated zone component is excluded from the simulation.

The lower boundary of the lowest layer is always considered as impermeable.

Boundary conditions can either be specified on the catchment boundary which is determined by the catchment grid code data file or in internal elements either defined by the catchment grid code data file or - for time-varying flux boundary -by the location of abstraction or injection wells. Table 4.1 gives an overview of boundary conditions and code values which can be applied in each layer of the setup.

Table 4.1 Boundary conditions.

Boundary Conditions			Valid in	
No.	Description	Code value	Boundary elements	Internal elements
1	Impermeable	0	x	
2	Constant potential head	2	x	x
3	Constant flux	3	x	
4	Constant gradient	4	x	
5	Time-varying potential head	5	x	x
6	Time-varying flux	-		x

If the boundary condition (5) is applied you should specify the name of the data file which contains time-varying values of potential heads in the edit field called "hbd-file". The data file is binary and formatted and can be produced by the post- processing programme MSHE.BND described in the PP-manual, Section 4.4. This tool extracts calculated potential heads from a regional MIKE SHE simulation to the boundary of a local MIKE SHE simulation. A head boundary file can also be produced from measured potential heads by the POD2HBD program described in the PP-manual, (Chapter 7).

If boundary condition (6) is applied you should specify the name of the data file which contains the location of the abstraction wells and the abstraction rates in the edit field called "Abstractions".

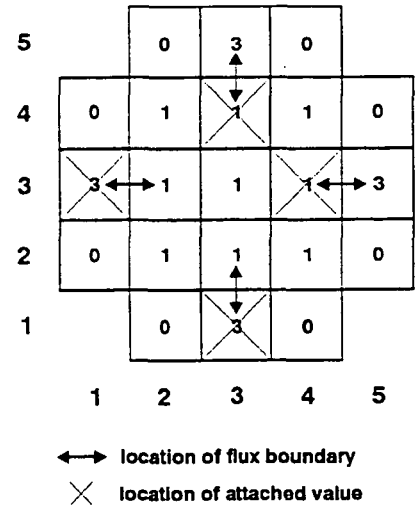
If one of the other boundary conditions is applied there are two possibilities in the edit field called "boundary grid code file":

(1) if the same boundary condition is valid for all boundary elements you just specify the code value for this boundary condition in the edit field;

(2) otherwise you should specify the data file name of a grid code data file which contains the spatial distribution of each of the boundary conditions;

If you have applied boundary condition (3) or (4) you continue and specify a uniform flux (or gradient) or data file names on data files containing spatial varying values of fluxes (or gradients). Constant potential head is assumed to be the initial potential head specified in menu F.1.4.

The figure below illustrates the location of a flux boundary (code 3) and specification of the attached flux in a T2 file. The arrow shows where the flux boundary is applied in the model. The x indicates where the attached flux value should be specified. For gradient boundaries (code 4) the same codes and values must be specified. Fluxes are positive in positive x and y direction. A positive gradient indicates increasing head in positive x and y directions.



Drainage

Drainage flow in MIKE SHE may cover artificial drainage and natural drainage which is not described in details in the river setup. Drainage flow is simulated by an empirical formula which for each element requires a level of the drain and a time constant for routing the water out of the element. The drains should always be located in the top layer. Drain levels (m) and time constants (s^{-1}) can as usual be specified as uniform values or as spatial varying values by type 2 data files.

Typical values for the level of artificial drains and the time constant is 1 m below surface and $1e^{-6}$-$1e^{-7}$ s^{-1} respectively.

When running the MIKE SHE setup program a reference system is made which links each single computational grid in SZ to a drainflow recipient. The drainflow recipient may be a river node, a lake (another SZ grid) or drainflow may be exported through the model boundary. Whenever drainflow is produced during a model simulation, the computed drain flow is routed from the drainflow producing grid to the reference point (recipient) using a linear reservoir routing technique as described in the MIKE SHE WM reference manual. A number of different options for setting up the reference system is available.

Option 1 - Drainage Reference system based on slope of the drains (Levels)

This option was originally the only available option in MIKE SHE. The reference system is made using the slope of the drains calculated from the drainage levels defined in Menu F.1.6 (see Fig. 4.16) Thus as long as a downward slope is found the drainflow will continue until crossing a river or the model boundary. Subsequently, a link is made from the drainflow producing grid to the river node or the model boundary. If local depressions in the drainage levels exist in a certain SZ grid, this SZ grid may become recipient for a number of drainflow producing grids. This often results in creation of a lake at such local depressions. This drain slope based reference system has been used in MIKE SHE for several years and works fine in most situations. However, when MIKE SHE is applied in flat terrain with very small surface topographic slopes it is often difficult to establish a suitable reference system. In many cases is may just be assumed that the drains are located e.g. 1 meter below terrain. In flat areas, this may however generate many undesired local depressions, which may receive drainage water from a large area, thus generating lakes at places where there should not be a lake. It should be noted that MIKE SHE consider a grid point to be a local depression even if the drainage level in the 4 surrounding model grids is only 1 mm higher. If the reference system is based on the slope of the drains the only way to avoid such effects is to create a drainage level map which does not contain "wrong" local depressions. For large model set-up's this may be a difficult and time consuming task and one of the other drainage options may be considered (described below).

Option 2 -Drainage Reference system based on grid code values (Codes)

This MIKE SHE drainflow option is often more feasible in the situations described above or whenever the drainage schemes are well defined and drain flow directions are known.

The new option involves specification of the following data:

- Drainage levels (as for the Original option)
- Time constants for routing of drainage water (as for the Original option)
- A grid code map (drain codes) which links drainflow producing grids to a recipient (New)

If the *code* option is selected in the MIKE SHE Menu F.1.6 either a T2 code file (type 21 integer code file) or an integer number must be specified in the *draincode* field. The file contains grid codes which define the drainflow reference system. In the draincode option the drainage levels are still used to calculate the amount of drainflow produced in each single computational grid. The drainflow reference system is however based only on the code values in the draincode file - not on the slope of the drains. In the draincode file an integer draincode must be specified in each model grid. The code values may be any integer number or equal to zero. Grids with code value zero will not produce any drainflow and will not receive any drainflow. All grids with code value 1 or more will produce drainflow to either river, boundary or a local depression in the drainlevel - in that priority. Grids with draincode larger than 0, e.g. draincode 1, will drain to the nearest river link located next to a grid with same drain code, in this case draincode 1. If no grid with the same draincode is located next to a river, the boundary is examined, and the drainflow will be routed to the nearest boundary grid with the same draincode. If no boundary grid holds the same draincode all grids with the same draincode are examined, and all drainflow is routed to the grid with the lowest drainlevel (which may create a lake). For grids with draincode values lower than 0 drainflow will be produced to either a boundary or a local depression. I.e. if a grid has a negative draincode, drainflow will take place to the nearest boundary grid with the same negative draincode if such one exist, otherwise the grid will drain to a local a depression or a boundary point using the slope of the drains. A number of examples on references between drainflow producing grids and drainflow recipients (river links, boundary and lakes) are illustrated in the figure below.

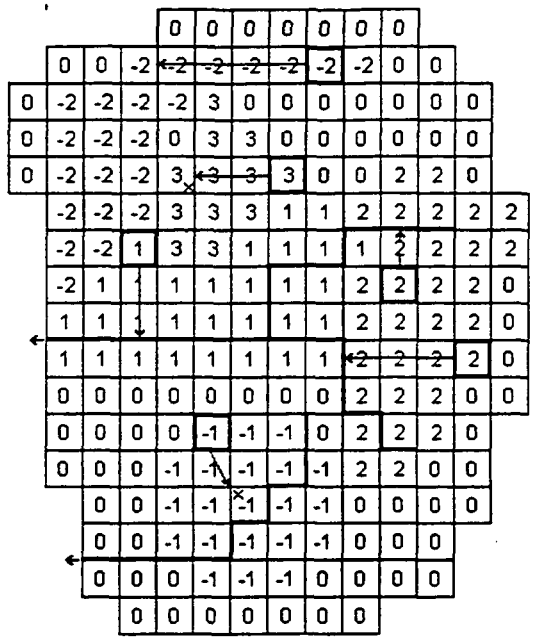


Fig 4.14 *Illustration of new draincode based reference system*

- grid with draincode 3 drains to local depression since no boundary or river link is found adjacent to a grid with the same draincode.
- grids with draincode 1 or 2 drains to nearest river link located adjacent to a grid with the same draincode.
- grids with draincode 0 does not contain drains and thus no drainflow is produced.
- grid with draincode -1 drains to local depression since no boundary is found adjacent to a grid with the same draincode.
- grid with draincode -2 drains to nearest boundary grid with the same draincode.

An option which may often be used is to specify only one draincode within the entire model area, e.g. draincode 1. This will imply that all grids may produce drainflow and that drainflow is routed to the nearest river link. If the setup does not have any rivers the drainflow will be routed to the boundary. If the intent is to route all drainflow to the boundary a negative draincode can be specified for the entire areas, e.g. draincode -1. An easy way to produce the draincode file is to modify an existing integer code file in MIKE SHE's T2-editor. In cases where detailed drainage network plans are available each drainage catchment may be digitised and given a certain code. Subsequently the draincode file may be produced using MIKE SHE's overlay maker (MIKE SHE OL).

Option 3 -Drainage Reference system combining option 1 and 2 (Levels & Codes)

A combination of the two above options can also be applied. To make a combination of the two drainflow routing options a type 21 integer T2 file must be specified in the field *distributed option* on Menu F.1.6. This file contains 2 code values, 1 and 2 respectively. All grid points with code value 1 will use option 1 and grid codes with code value 2 will use option 2.

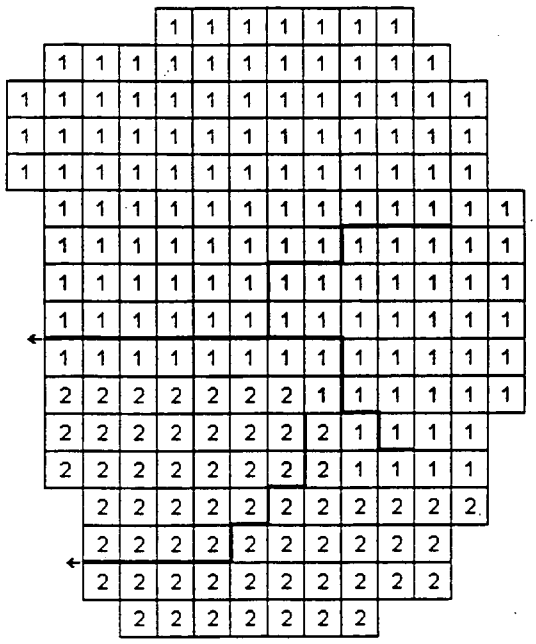


Fig.4.15 *Illustration of distribution combined use of drainflow routing option 1 and 2.*

Option 4 -Drainage to River and Boundaries only (Direct to boundary)

The fourth option is in principle identical to option 2 (codes), but does not allow drainage to an internal model point (lake). Thus, all grid points which does not drain to a river will drain to the model boundary.

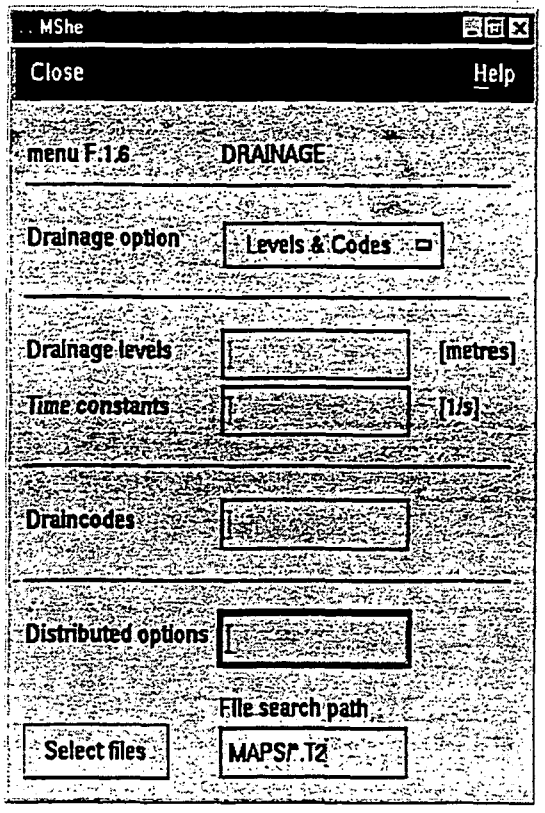


Fig.4.16 *Menu F.1.6 for specification of drainflow levels and reference system.*

4.4.1 Inspecting the drainage system

The utility program "Input Retrieval" provides the opportunity to retrieve two maps with information about the drainage system in the category "Other Maps" in menu U.2.

SZ drainage to local depressions and boundaries

This map shows the routing of drain water to local depressions and boundaries. Cells from where drainage occur has a negative code and cells with the same negative drains to the same point. If drain water is routed to a local depression the receiving cell will have a positive code. I.e. cells with –3 drains to the cell with 3. If drain water is routed to a boundary no receiving cell is shown. I.e. there is no corresponding positive number.

SZ drainage to river

This map shows the routing of drain water to rivers. A cell that drains to a river has a positive number and the receiving river link is identified by a negative code in an adjacent cell. I.e. cells with –5 drains to a river link that is located adjacent to the cell with 5.

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4.5 Evapotranspiration Component

MIKE SHE offers you two different codes for calculation of the actual evapotranspiration i.e. the Kristensen and Jensen model and the Penman-Monteith model. For the time being only the Kristensen and Jensen model is implemented, in the graphical user interface. Penman-Monteith requires specification of a number of parameters in a separate text file. (Not documented in this manual).

Kristensen and Jensen

In the model the actual evapotranspiration is calculated on basis of the potential evaporation, the leaf area index and root depth for each vegetation type and a set of empirical parameters. The specification for this model is given in menu F.1.12 shown in Fig. 4.17.

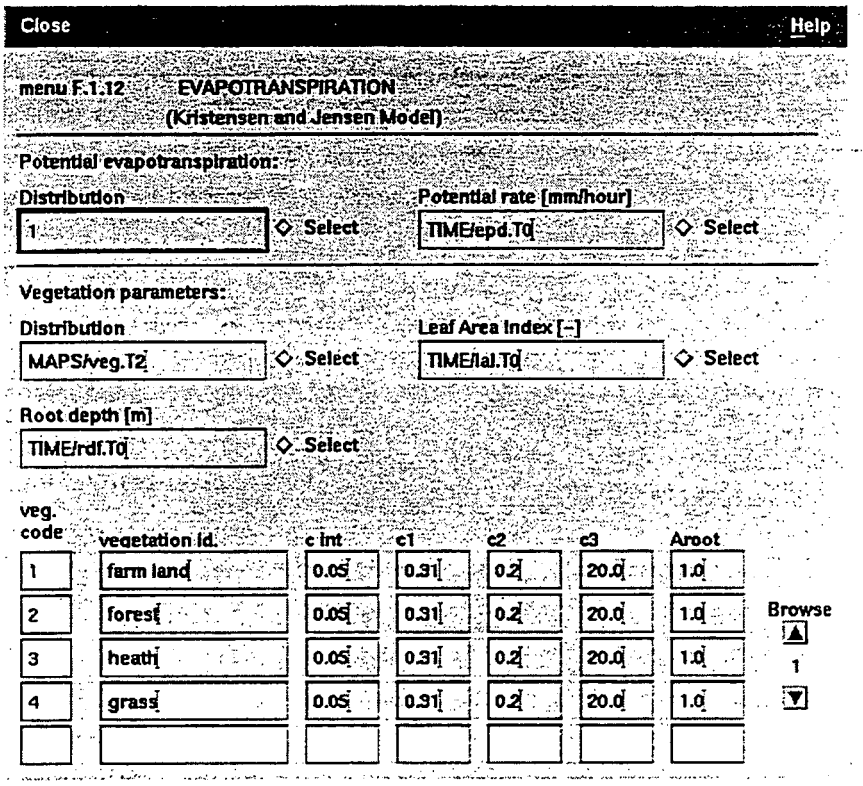

Figure 4.17 Definition of parameters for evapotranspiration.

Firstly, you should specify the potential evaporation - distribution in space of the different potential evaporation areas and in time of the potential evaporation rate. As usual the spatial distribution can be given as a name of a type 2 data file or a single value which refers to the record number in the time series data file. The distribution in time of potential evaporation can also be given as a name of a type 1 data file or as a single value valid through the entire period. The potential evaporation is specified in mm/hour.

Secondly, you should specify the vegetation - distribution in space of the type of vegetation and in time of the leaf area index and the root depth. The procedure is the same as explained above. Leaf area index is defined as the area of the leaves relative to the surface area and the root depth is given in metres.

4.6 Snow Melt Component

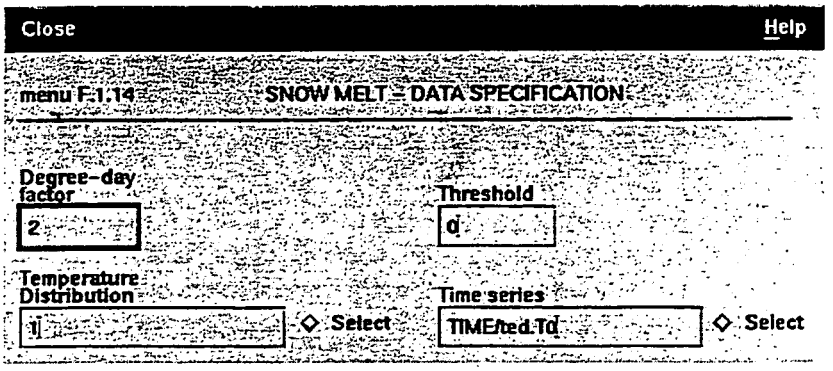

Figure 4.18 Definition of parameters for snow melt.(5)

Snow melt is calculated on basis of the degree-day method which only requires the temperature, a degree-day factor (mm snow/s/°C) and a threshold temperature defining the temperature at which melting occurs (usually 0°C). The specifications are given in menu F.1.14 shown in Fig. 4.18.

Firstly, specify the degree-day factor and the threshold temperature.

Secondly, you should specify the temperature distribution in space and time. The procedure is the same as previously described, i.e. distribution in space can be specified as a type 2 data file or as a single value which refers to the record number in the time series data file and the distribution in time can be specify as a single value or as the name of a T2-file.

4.7 "Dummy" Component

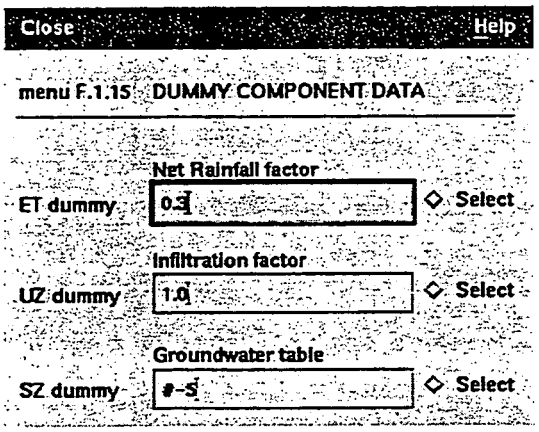

Figure 4.19 Definition of parameters for the "dummy" components.

If a MIKE SHE simulation does not include the evapotranspiration component, the unsaturated zone component or the saturated zone component then "dummy" components are applied instead. The specifications for the dummy component are given in menu F.1.15 (see Fig. 4.19).

4.7.1 Net Rainfall factor

If the ET component is not included in the setup you must specify the fraction of the total rainfall which enters the model (net rainfall). A constant value or a T2 file with distributed values may be specified. The value must be between 0-1. If the UZ model is included the net rainfall is input to the ground surface. Some of this water may then infiltrate through the unsaturated zone or create surface runoff. If the Overland Flow component is the only included component the net rainfall is considered as input to the OC flow calculation and no infiltration will occur.

4.7.2 Infiltration factor

If the saturated zone is included in the simulation and unsaturated zone is not included in the simulation you must specify the fraction of net rainfall (infiltration) that enters the model as direct recharge to SZ. If recharge to SZ equals 80 % of net rainfall the Infiltration factor is set to 0.8. The remaining fraction of net rainfall is input to ground surface where it may infiltrate using the saturated conductivity or where it may generate overland flow.

4.7.3 Groundwater table

The SZ dummy component is simply a ground water table (constant value or distributed in a T2 file). The ground water table will then serve as lower boundary condition for the UZ calculations.

4.8 Simulation Parameters

Before you can run the MIKE SHE model you have to specify some parameters, which controls the simulation i.e. the simulation period, the simulation time step, which data to store and storage time step etc. This is done in menu F.2, F.2.a and F.2.b.

4.8.1 Simulation control parameters

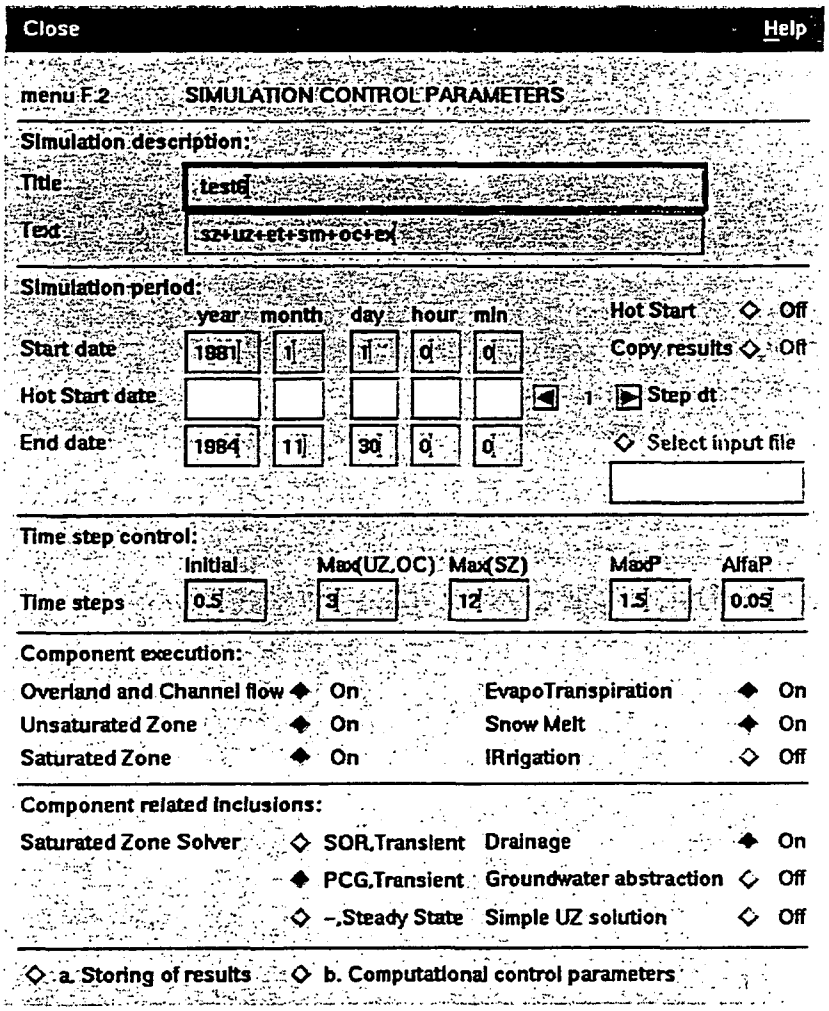

Figure 4.20 Specification of simulation control parameters.

Each simulation is given a title and additional text to describe the simulation. The title will appear on plots of simulation results. The simulation period is specified by a start date and an end date defined by year, month, day hour and minute. MIKE SHE checks the actual time and reads all the data given as time-series (precipitation, evaporation etc.) as the simulation goes on.

Simulation time steps in some of the component can be different and should be given in the edit fields under "time step control".

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The simulation time step in the components for UZ, OC and ET -dt - is controlled by "Max(UZ,OC)", "MaxP" and "AlfaP": If the precipitation in one time step is less than MaxP the time step is defined solely by Max(UZ,OC) which is specified in hours. If MaxP is exceeded in one time step the step will be reduced with the factor MaxP/ActualP. After a reduction the time step will increase with 100 * AlfaP% until Max(UZ,OC) is reached again. Typical values for Max(UZ,OC), MaxP and AlfaP are 2 hours, 1 mm and 0.05 respectively if the UZ component is included in the simulation and 48 hours, 50 mm and 0.05 respectively if only the SZ component is included in the simulation.

The simulation time step in the SZ component - dtSZ - is mainly controlled by "Max(SZ)". If one of the components UZ, OC or ET is included in the simulation the ratio dtSZ/dt will always be equal to Max(SZ)/Max(UZ,OC) i.e. if dt is reduced then dtSZ is also reduced. Max(UZ,OC) must be less than or equal to Max(SZ) and Max(SZ) must be an integer multiplum of Max(UZ,OC).

A MIKE SHE simulation can include combinations of different components. The components are included in a simulation by the toggles i.e. if you want the component to be included and the actual toggle is "Off" press the left mouse button and it is "On" and vice versa. Valid combinations of components are:

all components;
UZ, OC and SZ alone;
ET+UZ;
ET+UZ+OC;
ET+UZ+SZ;
SZ+EX+OC;

If you have included the SZ components in your simulation, it is possible to exclude simulation of drainage flow and groundwater abstraction - even if you have specified drainage coefficients and time series for groundwater abstraction.

From MIKE SHE version 5.24 a new solver for the ground water flow is included. The original solver (SOR - Successive Over Relaxation) is still available but the new solver (PCG - Preconditioned Conjugate Gradient) is generally more efficient. Thus, the PCG solver is recommended. The PCG method also runs in steady-state mode. This mode is however only applicable for pure ground water models (SZ only).

For the UZ model two simulation modes is available. Both of them are based on Richards equation but the simple UZ model ignores the very unlinear tension term of Richard's equation. This illuminates stability problems in the UZ model and enables a more coarse discretisation in time as well as in space. For many catchment scale studies the simple solution will be sufficient. However, in areas where capillary rise is important (fine textured top soils) the simple solution may underestimate the actual evapotranspiration rate.

Storing of results

Specifications for storing of results are given at menu F.2.a. which will appear if you press the toggle "a. Storing of results", see Fig. 4.21.

The simulation results are divided in groups - one group for results from ET, SM, and UZ, one group for water balance results, one group for results from SZ, one group for results from OC and one group with miscellaneous results which are necessary for simulation with the advection dispersion (AD) add-on module.

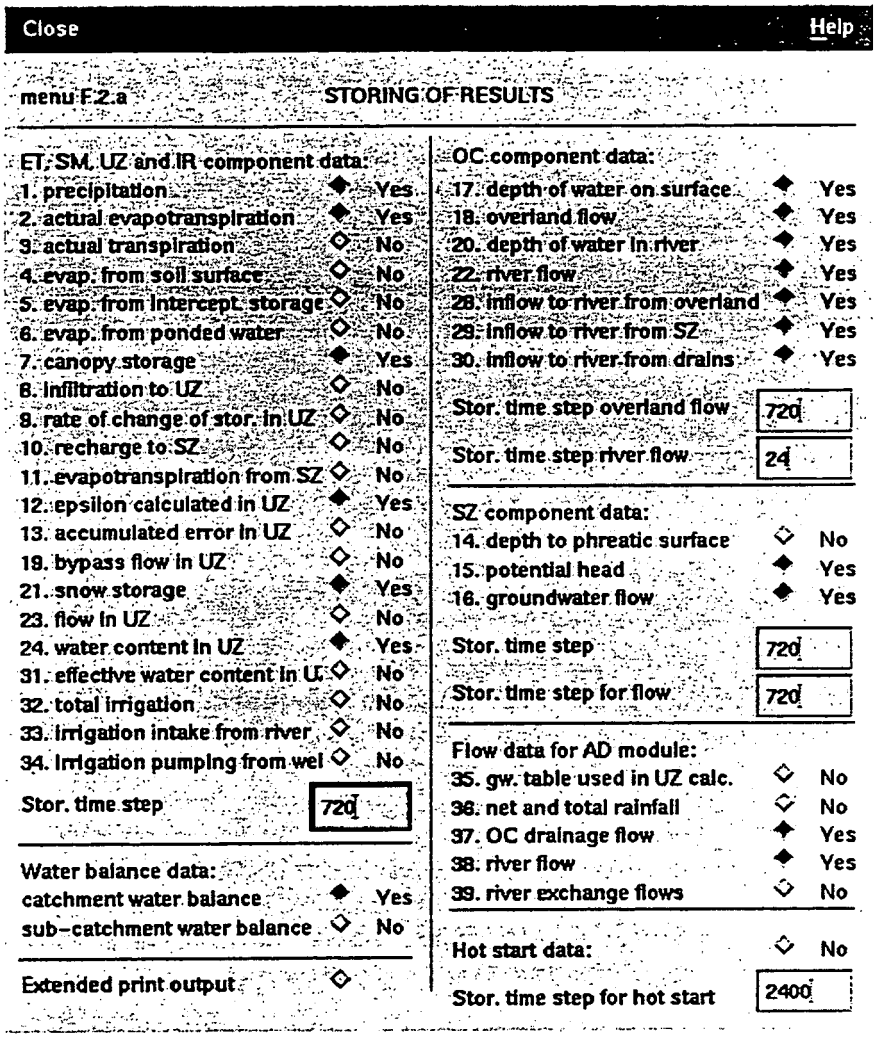

Figure 4.21 Storing of results.

Within each group the parametric results are stored on the result data file if the actual toggle is "Yes". Change between "Yes" and "No" by pressing the toggle with the left mouse button.

The storing frequencies are specified in hours. For results from the ET, SM, and UZ group and the OC group the storing frequency must be an integer multiplum of Max(UZ,OC). For results from the SZ group the storing frequency must be an integer multiplum of Max(SZ).

For the results from the OC component you can specify a different storing frequency for the river flow which is often measured on a daily basis and therefore should be stored at this frequency.

For the results from the SZ component you can specify a different storing frequency for the groundwater flow velocities than the other results from this component. In this manner you can save several megabytes of disk space on your result directory.

If you have problems with the model stability you can chose "Extended print output" and select a single element to be examined closer. Select the period in which you want print output of results from one or more components and you will get print output after each simulation time step of the selected variables. Be careful with your selected period since the print output data file quickly becomes rather large.

Computational control parameters

For each of the modules SZ, UZ and OC you have to specify a set of computational control parameters which controls the execution of the different iteration schemes. This is done in menu F.2.b, see Fig. 4.22.

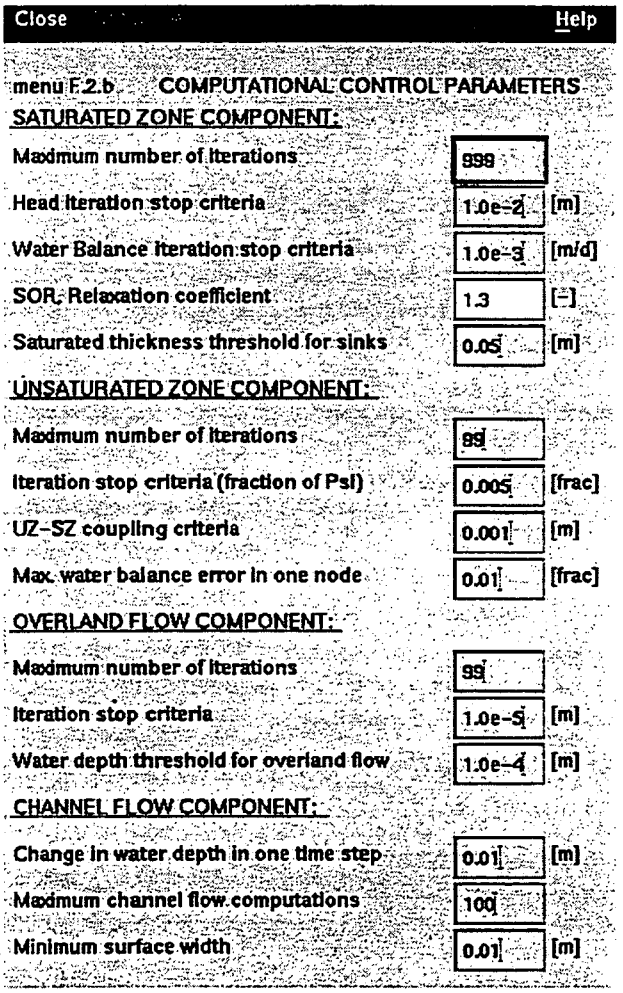

Figure 4.22 Computational control parameters.

Saturated Zone component

The potential heads and flow velocities in the saturated zone module are calculated in an implicit, iterative scheme. The iteration procedure can either be stopped when the interaction stop criteria is reached, i.e. the difference between succeeding solutions is less than this criteria in all computational elements, or when the maximum number of iterations in one time step is reached.

The iteration stop criteria consist of a mass balance criteria and a head criteria. Both criterions should be chosen carefully.

Mass balance criteria

Thus on one hand it should be low in order to avoid mass balance errors in your computation but on the other hand it should be large in order to minimise the number of iterations. A value around $1e^{-3}$ m/d is suggested in regional groundwater management studies. In small scale applications where transport and spreading of solutes is investigated the stop criteria must be smaller, for instance in the order of $1e^{-4}$ - $1e^{-5}$ m/d. In general it is recommended that rather high stop criteria is used during model calibration in order to ensure a reasonably short model simulation time. For production runs the stop criteria may be reduced in order to ensure a small mass balance error. In order to check if the stop criteria is reasonable the SZ water balance should always be checked after a simulation.

Head criteria

The head criteria determine the accuracy of the solution. The computational time is very depended of the chosen criteria. A value of 0.01 m is recommended in order to get a good representation of the dynamics of the groundwater potentials. During the initial model calibration a higher stop criteria can be used. The sensitivity of the head stop criteria should always be examined.

The speed of convergency also depends on the relaxation coefficient. Before you setup your model for a long simulation you should test the iteration procedure by a few short simulations with different relaxation coefficients. This coefficient must range between 1 and 2 and typical values are 1.3 - 1.6. The relaxation coefficient only applies for the SOR solver.

In order to avoid numerical stability problems the minimum depth of water should be defined larger than zero. When the water depth is computed to be less than this value in an element then the element is considered "dry" i.e. there is no flow of water out of this element.

Unsaturated zone component

The numerical solution in the UZ component uses an iterative procedure. Convergence is obtained when the changes in ψ between two iterations becomes less than PSItol for all nodes. Recommended value of the iteration stop criteria is 0.02 m or less.

The tolerance criteria in the UZ-SZ coupling procedure is the maximum allowed accumulated water balance error in one UZ column. If this value is exceeded the location of the groundwater table will be adjusted and additional computations in the UZ component will be made until this criteria is fulfilled. Recommended value is 0.002 m or less.

The maximum water balance error in one node is defined as the fraction of the total saturated volume in the node. The time step will automatically be reduced if the error is exceeded. Recommended value is 0.01 or less.

Overland flow and channel flow component

The iteration procedure applied in the overland flow component is identical to the procedure applied in the SZ module except that no overrelaxation is performed. The iteration stop criteria should be chosen carefully - as in the SZ component.

Here you can also specify the maximum number of iterations and the convergence criteria as well as the minimum depth of water on the ground surface at which overland flow occurs.

The channel flow component solves for the water depth in the river. The time step in the implicit numerical scheme is determined by the change in water depth between two solutions; if the change is larger than the specified maximum change the time step is reduced in the succeeding computation. This procedure is repeated until the specified maximum number of computations in the channel flow component compared to the overland flow component is reached.

The minimum surface area is a parameter which has the same meaning as the minimum depth in the saturated zone component.

5 Running MIKE SHE

Setting up your Model

Having completed all the tasks listed in the above sections and saving your specifications in a file (called the file selection file [fsf] you are now ready to "Set Up" the model. In the MIKE SHE terminology this means to merge all the specifications given above into a flow input file (the **fif**) binary formatted which can be read by MIKE SHE. For this purpose a utility program has been developed. This program includes an extensive check of data and parameters and is executed by choosing "Execute setup Program" and afterwards specify the file selection file as input file.

Calibrating and validating a MIKE SHE model

It is important to recognise that MIKE SHE WM requires calibration if it is applied on a different scale from that for which the equations have been developed and the parametric data are representative. In this connection it is also important to realise the representativeness of model output compared to measured values.

From the list given in section 3.2 it is obvious that it is impossible to collect data and parameters for each grid square or channel link. Furthermore, measured data represents most often a point or a very limited area while the model needs data which represents an average value over one grid square and/or average over some depth. It is therefore necessary to calibrate your model - but this must be done in a consistent way !

The purpose of the calibration is to tune the model so that it is able to reproduce measured conditions for a particular period in a satisfactory way. This period - known as the calibration period - should be chosen long enough to include events of similar kind as the ones you are going to investigate in your production simulations.

A satisfactory calibration is reached when the model is able to reproduce the measured values taking the following conditions into account:

- uncertainty in the measurements (time, space, equipment)
- representativeness of measurements (point/average grid values)
- differences between your conceptual model and nature
- uncertainty in other model parameters and data (precipitation, abstraction, etc.)

As indicated above it is impossible in general to specify an exact level of divergence between measured data and computed results before the model is satisfactorily calibrated. In each application you have to consider all factors influencing your result. After the calibration you should verify your model by running one or more simulations for which measurements are available without changing your model parameters. If the model is able to reproduce the measurements you can consider your calibration to be successful. Hence, it should be ensured, that simulations can be made for any period similar to the calibration and the validation period with satisfactory results.

As you have now a calibrated model you can get on with the "real" work, i.e. doing your actual investigations by running a set of production simulations.

6 Presentation of Results

Working with a distributed modelling system as MIKE SHE includes handling of large amounts of data - spatially and/or temporal varying. Much of the preparation of your data requires checking for inconsistencies and the best (and only) way to do this is to inspect them graphically.

Essentially, one plot gives more information than scores of tables and, if you can present them in colours, your message will be even more easily understood.

MIKE SHE includes a comprehensive graphical package for display of data and results. Much effort has been given to improve the capabilities for graphical presentation which in this version of MIKE SHE has resulted in a graphical editing tool which gives you a unique opportunity to check and modify spatial varying data and parameters. Reference is made to the MIKE SHE Pre- and Postprocessing manual.

MIKE SHE

Water Movement

Technical Reference Manual

Edition 1.1

MIKE SHE
Water Movement Module

PART II

Technical Reference Manual

Contents

MIKE SHE
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Technical Reference Manual

1 Frame Component

1.1 A General Description

The Frame component of MIKE SHE WM provides the controlling function to ensure an orderly and consistent execution of the other components and transfer of data between them. In brief it performs the following functions:

- o steers the reading of data for each component and the initialization of all computation variables
- o controls the sequence in which each component (perhaps dummy versions) is called to perform its computations, and controls the timesteps of the computations
- o controls the data flow from one component to another, i.e. processes the results of the computation in one component into the correct form for input to another component as internal boundary data
- o records a summary of the results at specified intervals on permanent storage, for further processing by post processing programmes.

The order, in which the frame carries out its functions is illustrated in Figure 1-1. First there is an initialization section, which calls the initialization routines for each component, including its own. These routines read all the relevant data and initialize the multitude of variables and arrays.

Then follows the section of the Frame where the sequence of calculations and controlling the flow of data between components is directed. Because of the close links between the evapotranspiration and interception (ET/IC), unsaturated zone (UZ) and snow melt (SM) components, the Frame calls only the UZ, which then calls the ET and SM.

The sequence of calling each component is illustrated in Figure 1-1 from left to right beginning with UZ.

One of the underlying principles in the modular construction of MIKE SHE is that it should be possible to replace any component with another version (e.g. updated, more comprehensive, simplified) without the need for changes in any other part of the system. This makes it possible to e.g. introduce "dummy" components for cases where one of the processes modelled is unimportant or even non-existent. These dummy components provide dummy results and ensure that the appropriate boundary flows are transferred between components, e.g. if the unsaturated/evapotranspiration computations are considered unimportant, a dummy component for this part could just transfer the net-rainfall direct to the groundwater table (SZ component) neglecting any timelag in the unsaturated zone.

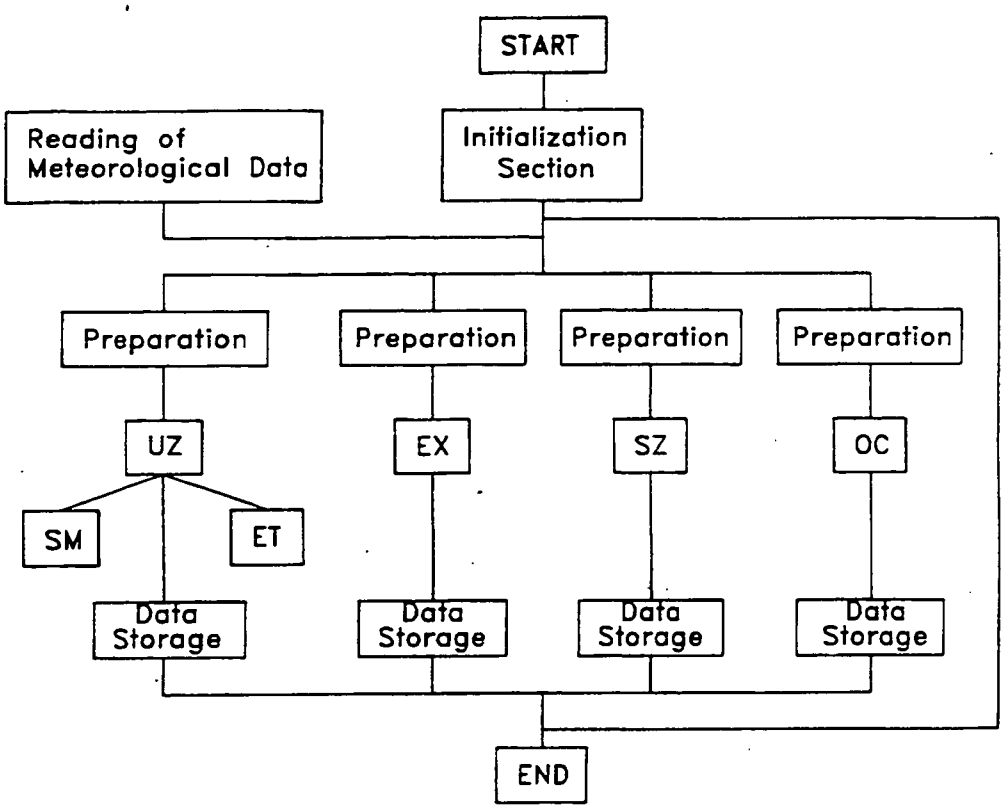


Figure 1-1 *Sequence by which each component is called in the Frame.*

1.2 Internal Boundary Conditions

Each component produces a large number of state variables and flow variables which are used by the other components to represent the entire hydrological cycle. In Table 1 is shown the required boundary variable for each component used in other components.

Table 1 *Internal boundary variables transferred between components in MIKE SHE WM.*

Variables	Component where the variable is used
Interception/Evapotranspiration (IC/ET)	
Net rainfall	UZ, OC
Soil evaporation	UZ
Transpiration	UZ
Bypass	SZ
Evaporation from groundwater	SZ
Evaporation from overland flow	OC
Unsaturated Zone (UZ)	
Infiltration	OC
Recharge to groundwater table	SZ
Saturated Zone (SZ)	
Groundwater table	UZ, EX
Seepage flow (FR)*	OC
Net groundwater flow in each gridsquare (FR)*	UZ
Overland and Channel flow (OC)	
Overland water depth	UZ, ET, SZ**
River water level	EX
Exchange Component (EX)	
Drainage Flow	SZ, OC
Discharge to river	SZ, OC

*) Calculated in Frame after SZ has been called

**) Used as initial condition for next SZ timestep if the groundwater table was above ground surface in previous SZ timestep and defined in FR.

1.3 Timestep Calculations

The time scale for different flow processes in a catchment varies. For example the surface flow component reacts much faster on a rainfall input than the subsurface flow component. An optimal timestep size (i.e. largest possible timestep without introduction of numerical errors) is different for the individual components. In addition the optimal timestep size varies in time as a consequence of different conditions in the hydrological regime within a catchment. During rather stationary (dry) periods the timesteps may be large compared to non-stationary situations during wet periods.

Preparations for allowing different timesteps in the different components have been made in MIKE SHE. The UZ, EX and OC overland flow components use identical timestep. MIKE SHE WM allows to specify larger timesteps for the SZ component since the results are less sensitive to timestep size in this component.
Figure 1-2 illustrates an example of the sequence of calling each component in MIKE SHE WM in which the timestep in SZ is twice as long as in the other components.

Figure 1-2 also illustrates the particular case during the simulation when data should be stored on disk or meteorological data read with specific time intervals.

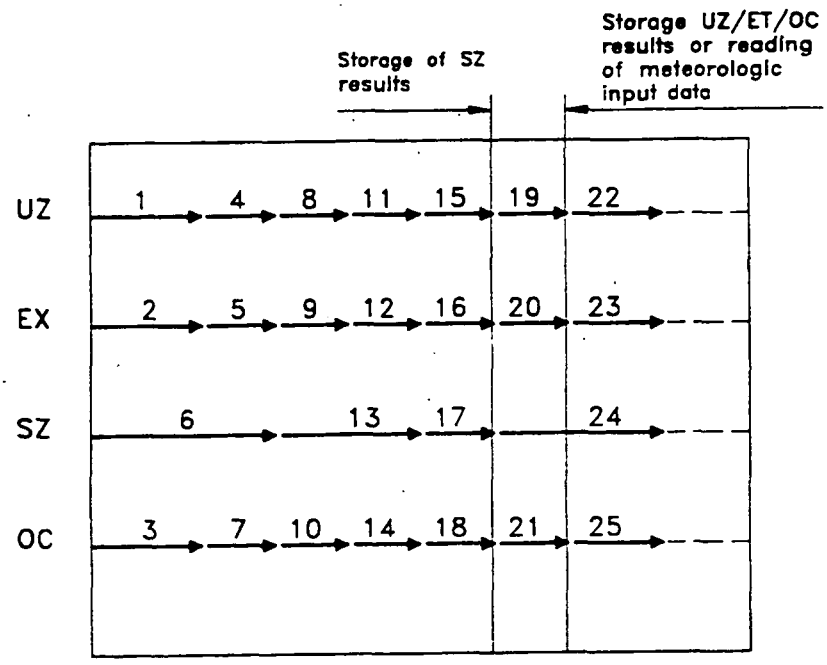


Figure 1-2 *Illustration of calculation sequence of the components in MIKE SHE WM.*

In the river routing routine of the OC component smaller timesteps (a fraction of the general timestep) can be applied in case of large simulated flow situations. The river routine reduces automatically the timestep size based on information about the maximum change in water level allowed during one timestep in any river node.

A variable timestep size sequence is available in MIKE SHE calculated in frame, and based upon the size of rainfall input. In the input data the following parameters are specified:

PMAX Maximum rainfall volume (mm) allowed in one timestep (hrs).

PALFA Rate of increase of timestep after reduction. The timestep is increased until the basic timestep TMAX is reached.

DHMAX Maximum river discharge (m^3/s) without reduction of timestep.

TMAX Basic timestep (hr).

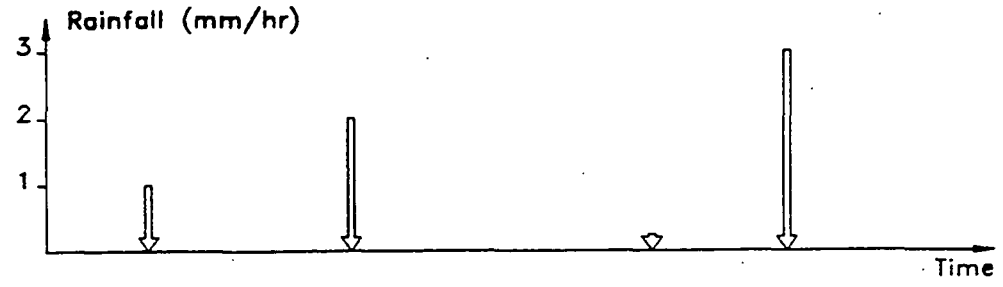
If the actual rainfall input P is larger than PMAX, the timestep is reduced in comparison to the basic timestep TMAX:

$$\Delta t = TMAX \cdot PMAX/P$$

The timestep Δt is constant during the entire rainfall episode and then increased at constant rate until the basic timestep TMAX is reached again or a new rainfall input calls for a new reduction:

$$\Delta t_{new} = \Delta t_{old} (1+PALFA) \text{ for } \Delta t_{new} \leq TMAX$$

In the calculations of the timesteps it is ensured that the actual time for reading the meteorological files or print of results are reached. This may occasionally require a reduction in the timestep. In Figure 1-3 is given an example of the timestep calculations. Note that a rainfall incident registered at time t_2 is covering the whole period between t_1 and t_2 e.g. P = 1 mm/hr at t_2 results in a total rainfall of $(t_2-t_1) \cdot 1$ mm.



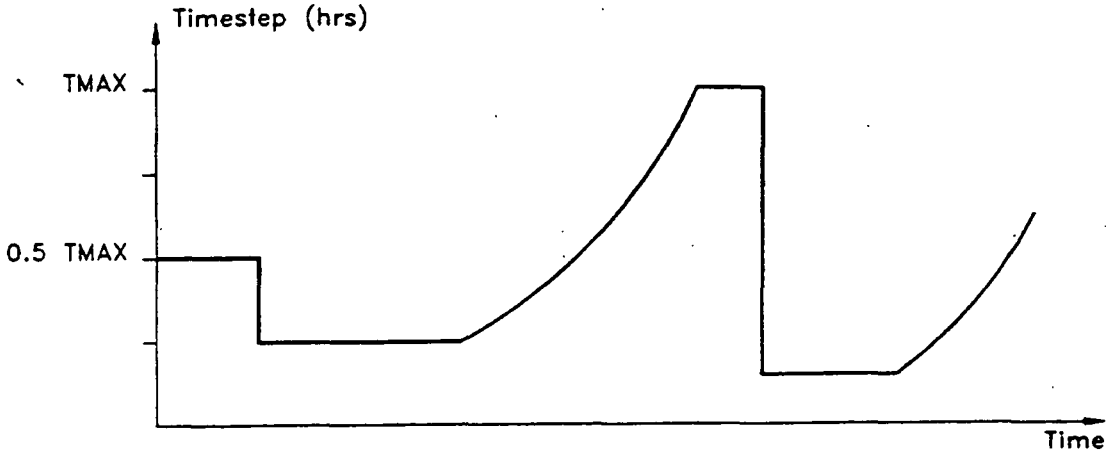


Figure 1-3 *Illustration of timestep calculation for UZ/OC/EX, P_{max} = 0.5 mm.*

2 Evapotranspiration and Interception Component

2.1 A General Description

The ET component uses meteorological and vegetative input data to predict, with empirically based equations and on a spatially distributed basis, the total evapotranspiration and net rainfall amounts resulting from the processes of:

1) Interception of rainfall by the canopy
2) Drainage from the canopy
3) Evaporation from the canopy surface
4) Evaporation from the soil surface
5) Uptake of water by plant roots and its transpiration

The component interacts with the unsaturated zone (UZ) component, providing net rainfall and evapotranspiration loss rates and using information on soil moisture conditions in the root zone. It is in general assumed that the temperature is above 0°C and that there is no snowpack.

In the basic model the processes are split up and modelled as follows. When rain falls, a proportion is intercepted by the vegetation canopy; a proportion may fall through the canopy to the soil surface or on the soil surface, where there is no vegetation. The intercepted water evaporates. The degree of vegetative coverage is described by the leaf area index LAI, and the interception is proportional to LAI. This means that throughfall of rain occurs when the interception storage is full. For sparse vegetation the interception storage capacity is low resulting in higher throughfall. Of the water in the root zone some is evaporated from the soil surface and some is taken up by the vegetation roots and transpired.

The model has been developed at the Royal Veterinary and Agricultural University in Denmark and published in Kristensen and Jensen (1975). The actual evapotranspiration is calculated on the basis of potential evaporation rate, which are required as input data, and the actual soil moisture status in the root zone. The derivation of the empirical equations in the model has been based on comparisons with actual measurements.

2.2 Evapotranspiration

The transpiration from the vegetation, E_{at} depends on the density of the crop green material, described by the leaf area index LAI, and the actual soil moisture content in the nodes in the root zone (Kristensen and Jensen (1975)). It also depends on the root density:

$$E_{at} = f_1(LAI)\ f_2(\theta)\ RDF\ E_P \qquad (2\text{-}1)$$

where

E_{at}	=	transpiration
RDF	=	root distribution function
f_1(LAI)	=	function shown in Figure 2-1
$f_2(\theta)$	=	function shown in Figure 2-2 and given by
E_p	=	potential evapotranspiration

$$f_2(\theta) = 1 - \left(\frac{\theta_F - \theta}{\theta_F - \theta_W}\right)^{\frac{C_3}{E_P}} \qquad (2\text{-}2)$$

where

θ_F	=	volumetric moisture content at field capacity
θ_W	=	volumetric moisture content at wilting point
θ	=	volumetric moisture content
C_3	=	empirical parameter (mm/day)

As illustrated in Figure 2-2, the C_3 parameter influences the value of $f_2(\theta)$ for a given soil moisture content θ. This means that for higher values of C_3 the transpiration will be higher at a given level of θ, which again means that the soil profile will dry out faster assuming other factors constant. In simulation results the user will see faster recession in the actual evapotranspiration curve during dry spells.

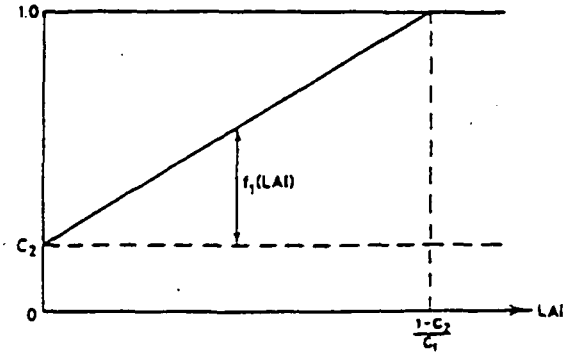


Figure 2-1 f_1(LAI) as a function of leaf area index LAI and the parameters C_1 and C_2.

Eq. (2-1) is applied to all nodes in the root zone. It is seen that the Eq. (2-1) includes a root distribution function RDF, which is calculated in the model assuming a logarithmic

variation with the depth in accordance with the usually distribution of the root mass. (See Root Distribution Function).

The soil evaporation E_s, taken only from the upper layers, consists of a basic evaporation $E_p\, f_3(\theta)$ plus evaporation from a possible water reserve in the upper layers, if a vegetation cover does not restrict the energy penetration to the soil surface

$$E_s = E_p\, f_3(\theta) + \left(E_p - E_{at} - E_p\, f_3(\theta)\right) f_4(\theta) \qquad (2\text{-}3)$$

$$\left(1 - f_1(LAI)\right)$$

where the functions $f_3(\theta)$ and $f_4(\theta)$ are given by

$$f_3(\theta) = \begin{cases} C_2 \dfrac{\theta}{\theta_W} \text{ for } \theta_M \le \theta \le \theta_W \\ C_2 \text{ for } \theta \ge \theta_W \\ 0 \text{ for } \theta \le \theta_M \end{cases} \qquad (2\text{-}4)$$

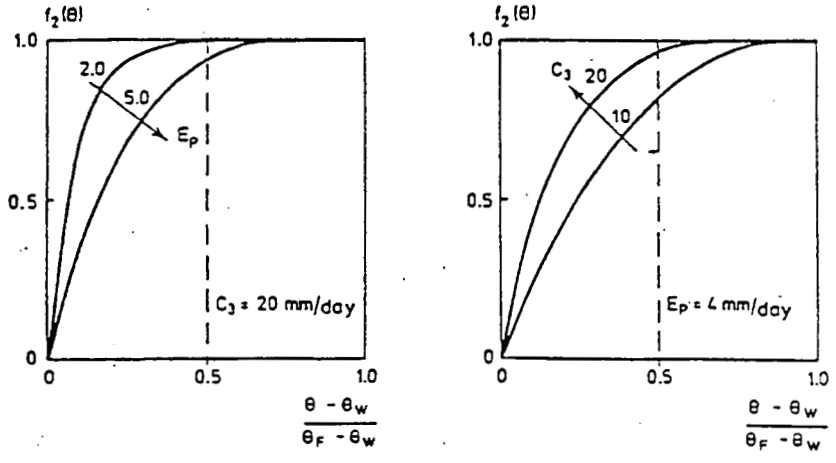


Figure 2-2 The soil moisture function $f_2(\theta_l)$ for constant C_3 (20 mm/day) and varying E_p (left), and for constant E_p (4 mm/day) and varying C_3 (right).

$$f_4(\theta) = \begin{cases} \dfrac{\theta - \tfrac{1}{2}(\theta_W + \theta_F)}{\theta_F - \tfrac{1}{2}(\theta_W + \theta_F)} & \text{for } \theta \ge \tfrac{1}{2}(\theta_W + \theta_F) \\ 0 & \text{else} \end{cases} \qquad (2\text{-}5)$$

The reduction E_s/E_p is a function of soil moisture in the upper layers as calculated from Eq. (2-4) and shown in Figure 2-3 in the case of $f_1(LAI) = 0$. In the model the soil evaporation is taken equally from the four upper most nodes.

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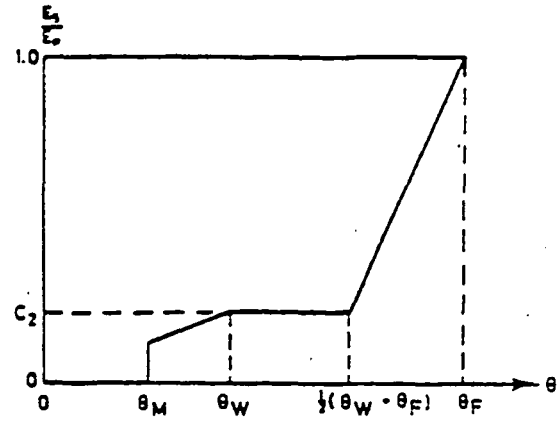

Figure 2-3 Soil evaporation E_s in relation to E_p as a function of soil moisture content, θ, in upper layers in the case of LAI = 0.

It is seen that the evapotranspiration routine contains three empirical parameters C_1, C_2, and C_3. The constants C_1 and C_2 for estimation of the transpiration function f_1(LAI) have for agricultural crops and grass, grown on clayey loamy soils, been estimated to .31 and .15 respectively. C_1 is purely plant dependent. C_2 may be slightly higher for more sandy soils with easier diffusion process. C_3 has not been evaluated experimentally. So far C_3 has been assumed equal to 10 mm/day. C_3 may depend on soil type and root density. The more water released at low matrix potential and the greater the root density the higher should the C_3 value be chosen. Further discussion is given in Kristensen and Jensen (1975).

The value of C_2 determines the distribution between soil evaporation and transpiration as shown in Table 2-1. It is seen that for higher values of C_2 a larger percentage of the actual evapotranspiration will take place as soil evaporation. Since soil evaporation only takes place from the top node (closest to the ground surface) in soil profile, the extraction from the top node gets higher weight as illustrated in Table 2-2. For example 23 per cent and 61 per cent of the total extraction takes place in the top node for C_2 values of 0 and 0.5 respectively.

The value of C_1 also influences the ratio between soil evaporation and transpiration. This is also illustrated in Table 2-1. For smaller C_1 values the ratio of soil evaporation becomes larger. For higher C_1 values, the ratio approaches the basic ratio determined by C_2 and the input value of LAI.

It can be concluded from the above that changing the C_2 value will influence the ratio between soil evaporation and transpiration, which again will influence the total actual evapotranspiration possible under dry conditions. With higher values of C_2 the total possible actual evapotranspiration becomes smaller because more water is being extracted from the top node, which subsequently dries out faster. The total actual evapotranspiration will therefore become sensitive to the capillary rise ability of the soil.

Table 2-1 The influence of the C_1 and C_2 parameters on the ratio (in per cent) between soil evaporation and transpiration. The figures have been obtained from model runs assuming C_{int}=0 and moisture content above field capacity (LAI=5).

C_1	C_2	Soil Evaporation (%)	Transpiration (%)
.31	0	0	100
.31	0.1	10	90
.31	0.2	20	80
.31	0.5	50	50
0.01	0.5	95	5
0.05		75	25
0.09		55	45
0.21		50	50
0.51		50	50
0.91	0.5	50	50

Table 2-2 Distribution of actual evapotranspiration (in per cent) over depth for different values of C_2. C_2=0 corresponds to pure transpiration.

	C_2			
Depth	0	0.1	0.2	0.5
5	22.9	30.6	38.3	61.4
15	18.15	16.3	14.5	9.07
25	14.4	13.0	11.5	7.2
35	11.5	10.3	9.16	5.72
45	9.1	8.18	7.27	4.54
55	7.23	6.50	5.78	3.61
65	5.75	5.17	4.59	2.87
75	4.56	4.10	3.65	2.28
85	3.62	3.30	2.9	18.1
95	2.88	2.60	2.3	1.43

2.3 Interception

Interception is defined as the process whereby precipitation is retained on the leaves, branches, and stems of vegetation. From there it evaporates without adding to moisture storage of the soil.

The interception process is modelled by introducing an interception storage, which has to be filled before throughflow to the ground surface takes place. The interception storage is diminished by direct evaporation.

The size of the interception storage capacity, I_{max}, depends on the vegetation type and its stage of development through the leaf area index LAI:

$$I_{max} = C_{int}\, LAI \qquad (2\text{-}6)$$

where

C_{int} = interception parameter (mm)
LAI = leaf area index

The parameter C_{int} is independent of vegetation type, but depends on the time resolution. On the basis of interception storage capacities given in the literature for different vegetation types, a typical value of C_{int} is 0.05 mm. The exact value may be assessed from calibration. The leaf area index LAI varies usually between 0 and 7.

2.4 Leaf Area Index

The coverage of leaves over an unit area of the ground surface is usually described by the leaf area index LAI. Usually generalised time varying functions for different crops are established. In MIKE SHE the user should specify the temporal variation in LAI for each crop (attached to a defined crop type) during the growing seasons to be simulated. Different climatic conditions from year to year may require a shift of the LAI curves in time but will generally not change the shape of the curve.

2.5 Root Distribution Function

The distribution of the water extraction for transpiration varies over the growing season. In nature the exact root development is a complex process which also depends on the climatic condition and the resulting moisture conditions in the soil.

MIKE SHE allows for a user defined time-varying root distribution determined by the root depth (time varying) and a general root density distribution in the vertical (Figure 2-4).

The extraction pattern R(z) is assumed to have a logarithmic variation with depth given by:

$$\log R(z) = \log R_o - AROOT z \qquad (2\text{-}7)$$

where R_o is the value at the soil surface, AROOT, describes the root mass distribution. The relative extraction for a node RDF is normalised with respect to the total extraction over the actual rooting depth L_R given by:

$$RDF_i = \int_{z_l}^{z_u} R(z)dz \,/\, \int_o^{L_r} R(z)dz \qquad (2\text{-}8)$$

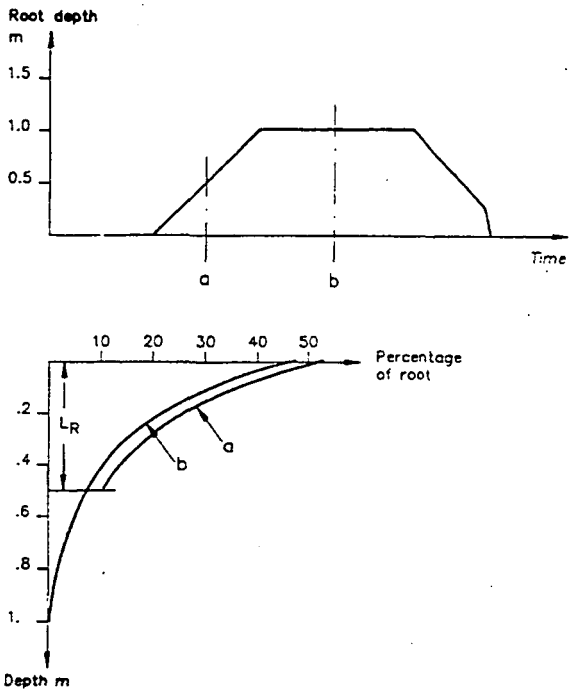

Figure 2-4 Root distribution in time and depth

The transpiration distribution over the depth of the soil depends on the AROOT parameter. Table 2-3 shows the distribution for different values of AROOT, assuming that the transpiration is at potential rate with no interception loss (C_{int}=0) and no soil evaporation loss (C_2=0).

It is seen from the table that the root distribution becomes more uniform distributed as AROOT approaches 0. In simulations the total actual transpiration tends to become smaller for higher values of AROOT because most of the water is drawn from the upper layer which subsequently dries out faster. The actual transpiration becomes therefore more dependent on the ability of the soil to conduct water upwards (capillary rise) to the layers with high root density.

Table 2-3 also shows the effect of the rooting depth (for equal value of AROOT). Smaller rooting depth will lead to small actual transpiration because a large portion of the roots is located in the upper parts of the profile.

The factors ARoot and rooting depth are important parameters for estimations how much water can be drawn from the soil profile under dry conditions.

Table 2-3 Distribution of transpiration (per cent) as a function of the value of AROOT.

	AROOT				
Depth (cm)	2.0	1.0 (root depth = 2.0 m)	0.5	0.1	1.0 (root depth 1.0 m)
5	36.9	20.8	12.1	6.17	22.95
15	28.2	16.5	10.8	6.03	18.15
25	14.7	13.1	9.60	5.90	14.4
35	9.27	10.4	8.55	5.76	11.5
45	5.85	8.77	7.62	5.63	9.1
55	3.70	6.57	6.80	5.50	7.23
65	2.32	5.22	6.06	5.37	5.75
75	1.47	4.15	5.40	5.25	4.56
85	.93	3.29	4.81	5.13	3.62
95	.59	2.62	4.29	5.01	2.88
105	.37	2.08	3.83	4.9	0
115	.15	1.65	3.40	4.79	0
125	.09	1.31	3.03	4.68	0
135	.06	1.04	2.70	4.57	0
145	.04	.83	2.41	4.47	0
155	.02	.65	2.14	4.37	0
165	.015	.52	1.91	4.27	0
175	.01	.41	1.70	4.17	0
185	.05	.33	1.52	4.08	0
195	0	.26	1.36	3.98	0
205	0	0	0	0	0

3 Overland Flow and Channel Flow Component

3.1 A General Description

When the net rainfall rate exceeds the infiltration capacity of the soil, water is ponded on the ground surface. This water is available as surface runoff, to be routed down-gradient towards the river system. The exact route and quantity is determined by the topography and flow resistance as well as the losses due to evaporation and infiltration along the flow path.

The water reaching the river system as surface and subsurface flow is routed downstream in a separate node point system. Both the overland flow and the channel flow are modelled by approximations of the St. Venant equations of continuity and momentum.

3.2 Governing Equation for Channel Flow

The equations governing flow in channels which are used in MIKE SHE are essentially one-dimensional versions of those described in the **Governing Equation for Overland Flow**. Suppose that the river flows in the x-direction, and that the bed level is $Z_o(x)$ and the depth of flow is h(x). Suppose further that the cross-sectional area of the flow in the channel is A(x), the flow velocity is u(x), and that there is a lateral inflow volume rate of $q_L(x)$ per unit length into the channel. Then conservation of mass gives

$$\frac{\partial A}{\partial t} + \frac{\partial}{\partial x}(Au) = q_L \qquad (3\text{-}1)$$

Once again, there is an equation of the St. Venant type which can be derived from the momentum equation. If we make the Diffusion wave approximation this may be simplified as:

$$S_f + \frac{\partial}{\partial x}(Z_o + h) = 0 \qquad (3\text{-}2)$$

where S_f is the friction slope.

Assuming a Strickler/Manning type law for the friction slope, with Strickler coefficient K, then

$$s_f = \frac{u^2}{K^2 h^{4/3}} \tag{3-3}$$

Hence the relationship between the flow Au and the cross-sectional area and depth may be written as:

$$Au = K\left(- \frac{\partial Z}{\partial x}\right)^{1/2} Ah^{2/3} \tag{3-4}$$

where $Z = Z_o + h$ is the water surface level referred to datum. The cross-sectional area A, and also the Strickler coefficient K will be functions of the depth h.

3.3 Governing Equation for Overland Flow

Using rectangular Cartesian (x,y) coordinates over the horizontal plane, let the ground surface level be Z_g (x,y), the flow depth (above the ground surface be h(x,y), and the flow velocities in the x- and y-directions be u(x,y) and v(x,y) respectively. Let i(x,y) be the net input into overland flow (net rainfall less infiltration). Then conservation of mass gives

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \tag{3-5}$$

There are two equations of the St. Venant type which can be derived from the x- and y-momentum equations. If we make the Diffusion wave approximation then these may be simplified as

$$S_{fx} + \frac{\partial}{\partial x}\left(Z_g + h\right) = 0 \tag{3-6a}$$

$$S_{fy} + \frac{\partial}{\partial y}\left(Z_g + h\right) = 0 \tag{3-6b}$$

where S_{fx} and S_{fy} are the friction slopes in the x- and y-directions respectively. If a Strickler/Manning-type law for each friction slope is used; with Strickler coefficients K_x and K_y in the two directions, then

$$S_{fx} = \frac{u^2}{K_x^2 h^{4/3}} \tag{3-7a}$$

$$S_{fy} = \frac{v^2}{K_y^2 h^{4/3}} \tag{3-7b}$$

Hence the relationship between the velocities and the depths may be written as

$$uh = K_x \left(- \frac{\partial z}{\partial x} \right)^{1/2} h^{5/3} \qquad (3\text{-}8a)$$

$$vh = K_y \left(- \frac{\partial z}{\partial y} \right)^{1/2} h^{5/3} \qquad (3\text{-}8b)$$

where $z = h + Z_g$ is the water surface level referred to datum. Note that the quantities uh and vh represent discharge per unit area in the two directions.

3.4 Initial Conditions

The initial conditions should be specified by the user in the input data files for the **MSHE.AF** service programme (ref. **MIKE SHE User Guide**). The user can read in maps (or default values) of the hydraulic head for each computational layer.

3.5 Lateral Inflow into a River

If a river flows between two overland flow squares, the water surface slope is calculated using the river bank level for the discharge on either side of the river, neglecting the water depth at the river banks.

If the bank level of the river is Z_B and the water surface levels and depths in the two neighbouring squares are Z_1,h_1 and Z_2,h_2, then the total discharge into the river is $Q_1 + Q_2$ where:

$$Q_1 = \frac{\sqrt{2}\, K_1 \Delta X}{\Delta x^{1/2}} \left(Z_1 - Z_B \right)^{1/2} h_1^{5/3} \qquad (3\text{-}9)$$

$$Q_2 = \frac{\sqrt{2}\, K_2 \Delta X}{\Delta x^{1/2}} \left(Z_2 - Z_B \right)^{1/2} h_2^{5/3} \qquad (3\text{-}10)$$

Note that these flows Q_1 and Q_2 should also be used for the appropriate ones out of Q_N, Q_S, Q_E, Q_W in Eq. (3-23) in **Spatial Resolution in Overland Flow** when calculating the new depths in the overland flow squares.

3.6 Looped Network

The OC algorithm allows also for simulation of channel flow in looped (or so-called multiply connected) network.

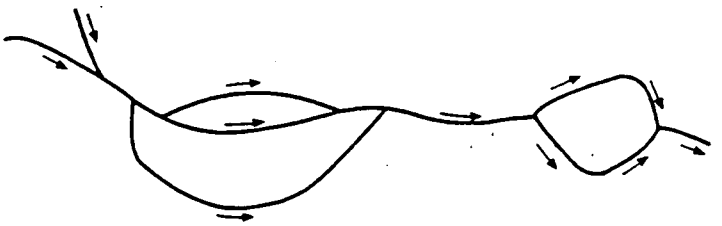

Figure 3-1 Example of 1-D looped river network

The cross-connection of a network is especially important in designing of irrigation or drainage hydraulic systems, modelling the catchments with non-uniform rainfall or the flow in the deviation channels during construction or maintenance works.

Basically there is no difference between the treatment of looped and branched (tree-like or arborescent) networks in the implicit algorithm of OC river calculations.

The implicit algorithm used for channel flow calculations enables to take into account the interconnected network, although some small instabilities in the first time steps can occur.

Note, that flood plains can not presently be modelled properly in the MIKE SHE.

3.7 Solution Method in Overland Flow

The method for solving the overland flow equations is similar to the method applied to the saturated zone flow. A linear matrix system of N equations with N unknowns is derived. The matrix is then solved iteratively, using the modified Gauss Seidel method, Thomas (1973). Because of the non-linear relationship between water levels and flows, the 2nd order term is included in the Taylor series expressing the correction of water levels as a function of the residuals.

As the flow equations so to speak are explicit during one iteration, it is necessary to reduce the calculated flows in some situations, to avoid internal water balance errors and divergence of the solution scheme:

Requiring that the water depth cannot be negative, implying $\Delta h \geq -h(t)$, Eq. (3-23) in **Spatial Resolution in Overland Flow** gives:

$$\Sigma Q \geq \frac{-I - \Delta x^2 h(t)}{\Delta t} \qquad (3\text{-}11)$$

where ΣQ is the sum of overland flows and river inflows.

Splitting ΣQ into inflows and outflows and remembering that outflow is negative, gives:

$$\Sigma |Qout| \leq \frac{\Sigma Qin + I + \Delta x^2 h(t)}{\Delta t} \qquad (3\text{-}12)$$

If necessary, the outflows initially calculated are reduced with a factor (0-1) to satisfy the equal sign of (2).

To ensure that the ΣQin has been counted before calculating ΣQout, the grid squares are treated in order of descending ground levels during each iteration.

3.8 Solution Scheme of Channel Flow

In the MIKE SHE WM model, the rivers are supposed to run along the boundaries of overland flow squares, between "nodes" at the corners of the squares. An ordering of these links and nodes is made during the initialisation phase of the operation of the program. There will be one such ordering for each disjoint river system in the data. To provide the ordering, the first node is found by scanning the grid south to north and from west to east along each line. Then look in the four directions from this node in the order S,W,N,E. The first node found is No. 2, the next (if any) No. 1 and so on. Next the four directions from node 2 are examined, then from node 3 and so on until the whole of the river system is defined. The process is repeated for each disjoint river system. Figure 3-2 shows how the ordering is applied.

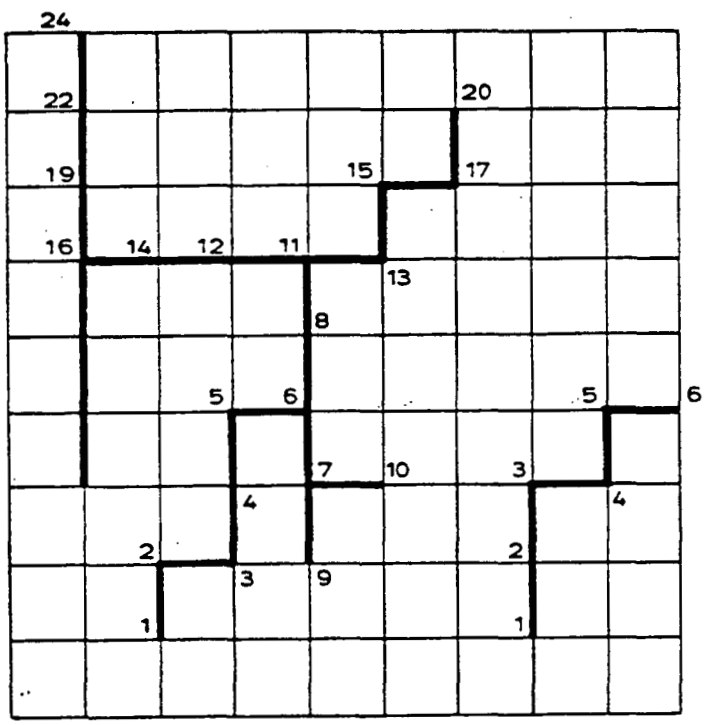

Figure 3-2 Example of OC river ordering.

There is a "band width" for the system, corresponding to the difference in node numbers for nodes which are adjacent. In the above example, nodes 16 and 20 are adjacent, so the band width is 5. It will be seen that the ordering used keeps this band width to a minimum, which is a useful feature when the matrix resulting from the finite difference scheme is solved.

Now consider the situation at one river node given in Figure 3-3. Without loss of generality, we can suppose that there are four river links at the node: if there are fewer, then the variables corresponding to the "missing" links may simply be regarded as zero. We may regard half of each of these river links as "belonging" to the node, and hence attribute half the water surface area and half the lateral inflow for each to the node.

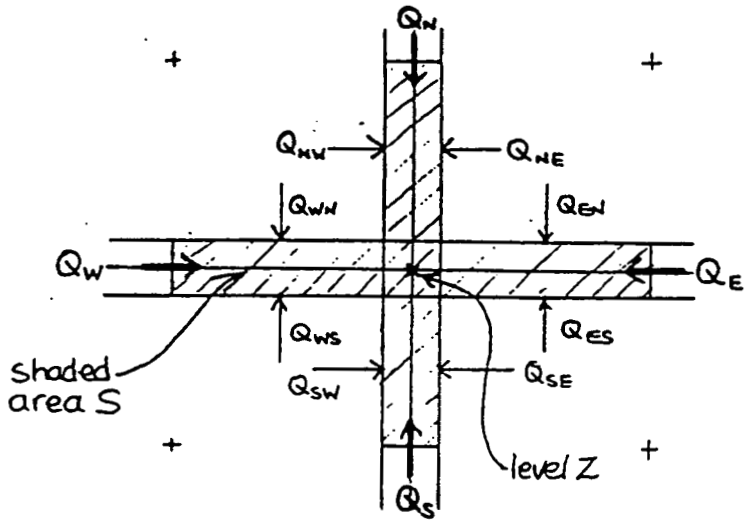

Figure 3-3 River node.

At the "top" end of a branch, the situation will be slightly different. The whole of the lateral inflow and surface area for the topmost link will be attributed to its downstream node, and no calculations are performed for the upstream node (no data are to be given for it either). The case of this top calculation node is otherwise the same as for any other node.

Consider the application of Eq. (3-13) over a reach with length L, width W, and mean depth d_m, where d_m and hence W are time-dependent. This means that $LA = d_m WL$ is the volume of water in the reach, and so if $S = WL$ is the water surface area of the reach,

$$\frac{\partial A}{\partial t} = \frac{1}{L}\frac{\partial}{\partial t}\left(Sd_m\right) \qquad (3\text{-}13)$$

Now consider the change between times t and $t + \Delta t$, supposing that the water surface level moves from Z to $Z + \Delta Z$ in that time. See Figure 3-4.

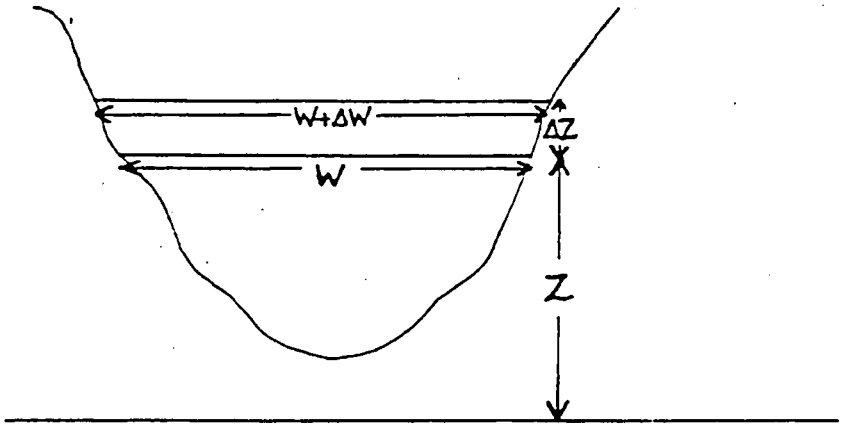

Figure 3-4 River cross section.

The change in Sd_m is the change in volume of water in the reach so

$$\frac{\partial A}{\partial t} \cong \frac{1}{L\Delta t}\left\{\frac{1}{2}\Delta Z\,(2W + \Delta W)L\right\} \tag{3-14}$$

and since we assume that the changes ΔZ and ΔW are both small,

$$\frac{\partial A}{\partial t} \cong \frac{S\Delta Z}{L\Delta t} \tag{3-15}$$

Thus, if the flows **into** the reach at the upstream and downstream ends are Q_U and Q_D, Eq. (3-13) may be approximated by

$$\frac{S\Delta Z}{L\Delta t} + \frac{1}{L}\left(-Q_D - Q_U\right) = q_L;\ \frac{\Delta Z}{\Delta t} = \frac{Q_D + Q_u}{S} + \frac{Lq_L}{S} \tag{3-16}$$

or

$$\Delta Z = \frac{\Delta t}{S}\left(Q_D + Q_U\right) + Q_L \tag{3-17}$$

where

$$Q_L = \frac{Lq_L}{S}$$

is the total lateral inflow into the reach.

Generalising to the node in the river system, it follows that the change in level ΔZ at the node is

$$\Delta Z = \frac{1}{S}\left(Q_N + Q_S + Q_E + Q_W + Q_R\right)\Delta t \_ \frac{\Delta Z}{\Delta t} = \frac{Q^{\bullet} + Q_R}{S} \tag{3-18}$$

where

$$Q_R = Q_{NE} + Q_{EN} + Q_{SE} + Q_{ES} + Q_{SW} + Q_{WS} + Q_{NW} + Q_{WN}$$

is the total lateral inflow, and Q_N, Q_S, Q_E, Q_W are the flows **into** the node region. ($Q^* = Q_N + Q_S + Q_E + Q_W$).

It remains to evaluate Q_N, Q_S, Q_E, Q_W. In the scheme chosen for MIKE SHE WM the evaluation is "fully-forward", i.e. at time $t + \Delta t$.

Take the flow in the northern link Q_N as an example. From equation (4), we see that Q_N is a function of Z and Z_N (where Z_N is the level at the northern node). Thus, using a Taylor series expansion to first order,

$$\left\{\frac{1}{S}\,Q_N\right\}_{t+\Delta t} \cong \left\{\frac{1}{S}\,Q_N + \frac{1}{S}\left(\frac{\partial Q_N}{\partial Z}\,\Delta Z + \frac{\partial Q_N}{\partial Z_N}\,\Delta Z_N\right) - \frac{1}{S^2}\,Q_N\,\frac{dS}{dZ}\,\Delta Z\right\}_t \quad (3\text{-}19)$$

Similar expressions may be obtained for Q_S, Q_E and Q_W, and by substitution in Eq. (3-18), we obtain the following equation:

$$\left\{\frac{\partial Q^*}{\partial Z} - \frac{Q^*}{S}\,\frac{dS}{dZ} - \frac{S}{\Delta t}\right\}\Delta Z$$

$$+ \frac{\partial Q_N}{\partial Z_N}\,\Delta Z_N + \frac{\partial Q_S}{\partial Z_S}\,\Delta Z_S + \frac{\partial Q_E}{\partial Z_E}\,\Delta z_E + \frac{\partial Q_W}{\partial Z_W}\,\Delta Z_W = \quad (3\text{-}20)$$

$$-\left(Q^* + Q_R\right)$$

where $Q^* = Q_N + Q_S + Q_E + Q_W$ is the total inflow into the node region.

Repeating the same procedure for all the interconnected nodes in one river system (in fact one can introduce many independent river systems in MIKE SHE WM) defines a linear system with equal number of unknowns and equations.

Thus an implicit finite difference scheme has been created for the changes in levels at the river nodes. It will now be seen that the choice of ordering for the river nodes means that a linear matrix equation is set up which can be solved for the unknown vector of ΔZ's, in which the main matrix of coefficients is a banded matrix where the bandwidth is kept to a minimum. It should also be noted that if there is no link from node i to node j, then the coefficient of ΔZ_j in the equation based on ΔZ_i and the coefficient of ΔZ_i in the equation based on ΔZ_j are both zero - this may be expressed by saying that the matrix of coefficients is "topologically symmetrical" i.e. the zeros are symmetrically placed but with different values in the other positions.

3.9 Sources and Sinks in the Channel Flow Component

Sources and sinks in the channel flow component are new possibilities incorporated in the MIKE SHE WM. Eq. (3-1) in the section about **Governing Equation for Channel Flow** is extended with a source/sink term, q_s, on the right hand side.

Sources/sinks can be given in different ways i.e. either as constant or time-varying fluxes or as so-called augmentation wells.

The latter implies that the user can specify a groundwater abstraction well as the source (or sink) and water abstracted from the saturated zone is lead to the specified location in the river network.

In some dedicated model setup's it is also possible to define an augmentation policy where the user defines river flows at which the augmentation wells should start and stop, respectively. This option is useful when regulation rules for the river have to be followed and the impact on groundwater storage and head is to be investigated. Refer to **MIKE SHE PP User Guide** to see the format of the data file to be prepared if this option is applied.

3.10 Spatial Resolution in Overland Flow

Consider the overland flow in a typical square (see Figure 3-5) of the MIKE SHE model, having sides of length Δx and a water depth of h(t) at time t.

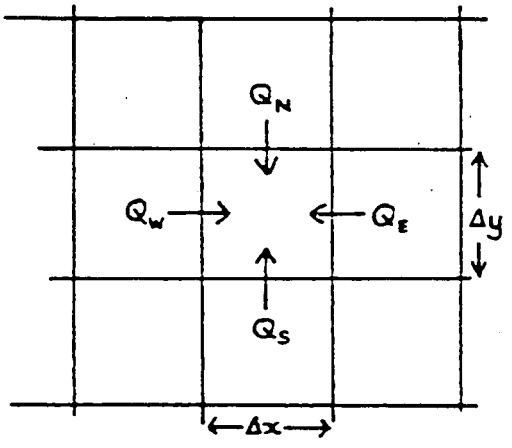

Figure 3-5 Discretization at rectangular grid

A finite-difference form of the Governing Equations may be derived from the approximations

$$\frac{\partial}{\partial x}(uh) \cong \frac{1}{\Delta x}\left\{(uh)_{east} - (uh)_{west}\right\} \qquad (3\text{-}21)$$

and

$$\frac{\partial}{\partial y}(uh) \cong \frac{1}{\Delta x}\left\{(vh)_{north} - (vh)_{south}\right\} \qquad (3\text{-}22)$$

where the subscripts denote the evaluation of the quantity at the appropriate side of the square, and noting that, for example, $\Delta x\,(uh)_{west}$ is the volume flow across the western boundary.

$$\Delta h = h(t+\Delta t) - h(t) = \frac{I + \sum Q\,\Delta t}{\Delta x^2} \qquad (3\text{-}23)$$

where

$$I = i\Delta x^2, \quad \sum Q = Q_N + Q_S + Q_E + Q_W \qquad (3\text{-}24)$$

and the Q's are the flows **into** the square across its north, south, east and west boundaries evaluated at time t.

Now consider the flow across any boundary between squares (Figure 3-6), where Z_U and Z_D are the higher and lower of the two water levels referred to datum. Let the depth of water in the square corresponding to Z_U be h_U and that in the square corresponding to Z_D to h_D.

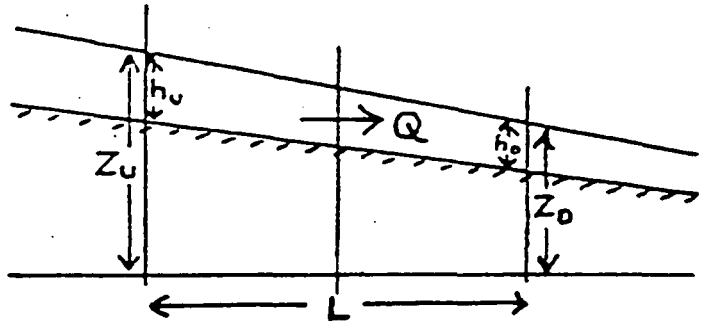

Figure 3-6 Overland flow across grid square boundary.

The Eqs. 3-8a and 3-8b in **Governing Equation for Overland Flow** may be used to estimate the flow Q between grid squares as

$$Q = \frac{K\Delta x}{\Delta x^{2/3}}\left(Z_U - Z_D\right)^{1/2} h_u^{5/3} \qquad (3\text{-}25)$$

where K is the appropriate Strickler coefficient. Note that the flow will be zero if the upstream depth is zero. The flow across open boundaries at the limit of the model is calculated in the same way, using the specified boundary water levels.

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4 Unsaturated Zone Component

4.1 A General Description

The Unsaturated Zone (UZ) Component plays an important role in the MIKE SHE WM as all other components depend on boundary data from UZ component. It links the two horizontal two- and three-dimensional surface and subsurface flow processes together. The evapotranspiration process utilizes also results obtained in the UZ.

The flow is described by the one-dimensional governing equation, the so-called Richards' equation. Soil water systems comprise three phases; solid, liquid and gas which introduce highly nonlinear terms in the Richards' equation. Knowledge about the soil physical properties are required in order to obtain a solution to Richards' equation.

The upper part of the unsaturated zone includes root extraction for the transpiration process. This is explicitly incorporated in the equation by sink terms. The integral of the sinks over the entire root zone depth amounts the total actual evapotranspiration. Soil evaporation is catered for in the first sink term below the ground surface. The interaction between the unsaturated- and saturated zone is solved by an iterative mass balance procedure, where the lower part of the UZ node system may be solved separately in a pseudo timestep, between two real timesteps. This coupling procedure ensures a realistic description of the water table fluctuations in situations with shallow soils. Particularly in these cases it is important to account for a variable specific yield above the water table. The special yield depends on the actual soil moisture profile and availability of that water.

Because the Richards' equation needs to be solved at every grid square in the model grid, the UZ component consumes a considerable part of the total computer time. In cases where homogeneous regions exist within the model area (identical vegetation- and soil types, and (nearly) identical boundary conditions) UZ calculations in the grid squares within each homogeneous region may be lumped together. This means that the UZ calculations are only performed in one representative column within the homogeneous region, and the boundary conditions from this column is then transferred to the other equivalent columns. This approximation is found appropriate and useful in a series of applications.

4.2 Boundary Conditions

The unsaturated zone extends from the ground surface to the groundwater table. The vertical flow is determined by the boundary conditions in each end of the zone.

The *upper boundary* condition at the ground surface determines the infiltration rate. Two conditions exist: 1) a constant flux within a time step at the surface arising from the rainfall rate and 2) ponded water at the ground surface. These two conditions correspond to the Neuman and Dirichlet boundary condition respectively.

If the infiltration is equal to the rate of rain R reaching the soil before ponding, Eq. (4-21) in **Solution Scheme** can be written for the top node N as:

$$C_N^{n+1/2} \frac{\psi_N^{n+1} - \psi_N^n}{\Delta t} =$$

$$\left(-R - K_{n-1/2}^{n+1/2}\left(\frac{\psi_N^{n+1} - \psi_{N-1}^{n+1}}{\Delta Z_N} + 1\right)\right) \frac{1}{0.5(\Delta Z_{N+1} + \Delta Z_n)} \qquad (4\text{-}1)$$

$$- S_N^{n+1}$$

where R is defined negative downwards. Written on similar form as Eq. (4-23) in **Solution Scheme**, Eq. (4-1) yields

$$A_N \psi_{N-1}^{n+1} + B_N \psi_N^{n+1} = D_N \qquad (4\text{-}2)$$

where

$$A_N = - K_{N-\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_-$$

$$B_N = C_N^{n+\frac{1}{2}} / \Delta t + K_{N-\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_- \qquad (4\text{-}3)$$

$$D_N = C_N^{n+\frac{1}{2}} \frac{\psi_N^n}{\Delta t} + \frac{-R - K_{N-\frac{1}{2}}^{n+\frac{1}{2}}}{\frac{1}{2}(\Delta Z_{N+1} + \Delta Z_N)} - S_N^{n+1}$$

If water is ponded on the ground surface, the first node is assumed saturated and the boundary condition simply becomes

$$\psi_N^{n+1} = \psi_N^n = \Delta Z_{N+1} \qquad (4\text{-}4)$$

During a storm event the flux condition is satisfied in the beginning of the storm as long as the infiltration capacity f_p is less than the application rate. As the moisture content increases in the upper part of the soil, f_p decreases and may become lower than the rainfall rate. At this time water is on the surface. In the model this change in boundary condition is managed by the following procedure: At the actual timestep when ponding occurs, the flux boundary will yield a ψ_N^{n+1}-value greater than ΔZ_{N+1}. This is checked by the program and the calculations are repeated using the pressure boundary instead, Eq. (4-4).The upper boundary is changing from ponding to a flux condition when the infiltration rate exceeds the available water stored on the ground surface. The calculations in this timestep are repeated using a flux boundary. The flux rate is equal to the water depth divided by the timestep.

The *lower boundary* condition is in most cases a pressure head boundary determined by the water table elevation. In this case Eq. (4-3) consists of N-M equations. If the node M denotes the first node below water table the boundary specifications read:

$$E_{M+1} = 0 \quad F_{M+1} = \psi_M^{n+1} = h \tag{4-5}$$

where h is the distance between the water table and node M. It is noted that ψ_M is independent of ψ_{M+1} since $E_{M+1} = 0$.

For a description of the dynamic coupling with the groundwater table reference is made to **Coupling of the Unsaturated- and Saturated Zones**.

In the MIKE SHE WM the lower boundary is automatically shifted from a pressure head boundary to a zero flux boundary (Q=0) if the water table falls below the impermeable bed and at same time there is an upward flux in the lower part of the profile. The head boundary is reentered as soon as a positive hydraulic pressure gradient is calculated or the water table is rising in the profile.

4.3 Coupling of the Unsaturated- and Saturated Zones

The recharge to the groundwater is determined by the actual moisture distribution in the unsaturated zone. A correct description of the recharge process is rather complicated because the water table simultaneously rises as water is entering the groundwater zone and therefore exerts a feedback on the flow conditions in the unsaturated zone.

The actual rise of the groundwater table depends on the moisture profile above the water table. On the other hand if a grid square receives a certain amount of net groundwater flow in a SZ time step the rise in water table depends not only on the available volume of air above the water table, but also on how the redistribution in the UZ takes place.

In case of rapid falling groundwater table the drainage in the UZ may be lagging behind and reach a equilibrium profile after a certain time interval that depends on the soil type.

The main difficulty in describing the linkage between the two zones arises from the fact that the two components are run in parallel and therefore not solved in an integrated form. In MIKE SHE WM this problem has been overcome by employing an iterative procedure based on a mass balance calculation for the entire column including horizontal flows in the saturated zone.

The procedure consists of a bookkeeping of the accumulated mass balance error E_{cum} for the entire grid square column. If $|E_{cum}|$ exceeds certain specified limits E_{max}, action is taken for adjustment of the water table and a redistribution of moisture content in the lower part of the UZ until $|E_{cum}| < E_{max}$. The error in the mass balance originates from two sources; 1) keeping the water table constant during an UZ-timestep and 2) using an incorrect estimate of the specific yield S_y (deficit between effective saturation θ_{sat} and moisture content at field capacity θ_{fc}) in the SZ-calculations. This is illustrated in Figure 4-1a). If we neglect the horizontal SZ-flow, it appears from the figure that during the time n n+m, the column has lost V_1 mm of water (the light grey shaded area and gained V_2 mm (the dark shaded area). The two areas are different because SZ uses the specific yield S_y in the catchment. The rise in the water table has therefore only balanced

the water loss to a minor extent. However, by adjusting the water table (see Figure 4-1b) in a pseudo timestep until the two shaded areas are equal a correct mass balance can be re-established.

The size of E_{max} determines the largest allowable mass balance before adjustments are made. Usually a value of e.g. E_{max} = 2 mm is appropriate.

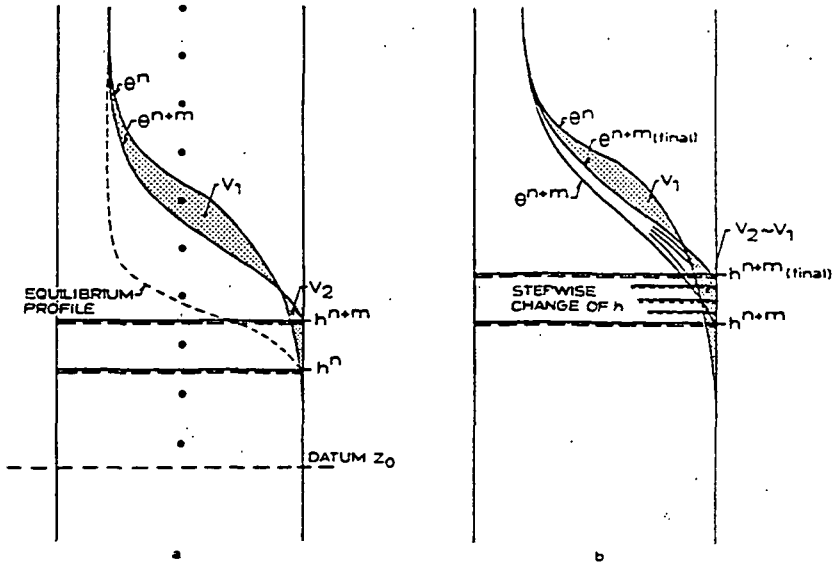

Figure 4-1 *a) Soil moisture content at two times n and n+m without corrections, and b) Soil moisture content at time n+m before and after correction.*

In the following the actual steps in the coupling procedure are given.

1. If the total water content above the datum Zo (Zo should always be lower than the lowest elevation of the phreatic surface) is designated Wn, the flow rate across the lower boundary in UZ-timestep n n+1 is

$$q_u^{n+1} = \left(W^{n+1} - W^n\right) / \Delta t^{n+1} + q_I + q_E \qquad (4\text{-}6)$$

where Wn+1 = the new water content; qI = the infiltration rate (negative downwards); qE = the evapotranspiration loss. (Note: qu < 0 downward flow).

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2. Assuming that the horizontal groundwater flow q_G is steady (positive outwards) the accumulated error at time n+1 is:

$$E_{cum}^{n+1} = \left(q_u^{n+1} + q_G\right)\Delta t + E_{cum}^{n} \qquad (4\text{-}7)$$

It should be noted that if $E_{cum} < 0$ too little water is stored in the column and if $E_{cum} > 0$ too much water is stored in the column.

3. If $|E_{cum}^{n+1}| < E_{max}$ the error in the water balance is too small for corrections, and we proceed to the next SZ-timestep n → n+1 by solving the SZ differential equation with the recharge term q_u^{n+1}

4. If $|E_{cum}^{n+1}| > E_{max}$ the following corrective steps are made:

   a) If $|E_{cum}^{n+1}|$ is negative, the UZ-calculation in timestep n → n+1 is repeated for the four lowest node points where the water table is raised in prescribed changes depending on the node point distances.

   b) The pressure-head profile is recalculated using a zero flux boundary at the top-node of this four node system.

   c) The change in water content W^{n+1*} over the entire column is computed and a new $|E_{cum}^{n+1}|$ is calculated.

   d) If $|E_{cum}^{n+1}| < a\, E_{max}$ where $a \leq 1$, an acceptable error is obtained and the procedure stops. Otherwise steps a) to d) are repeated. The factor a is introduced in order to avoid that corrections need to be made in every timestep.

5. A new recharge rate q_u^{n+1} is calculated taking the adjustments into account.

$$q_u^{n+1} = -\left(h^{n*} - h^{n}\right) S_y / \Delta t \qquad (4\text{-}8)$$

where h^{n*} is the new water table elevation after step d) calculated by UZ. It is seen that if there happens to be no horizontal SZ-flow in the next SZ-timestep, the water table from the SZ calculation will be $h^{n+1} = h^{n*}$.
If $|E_{cum}^{n+1}|$ in step a) is positive the water table is lowered steps a)-f) are performed.

It should be noticed that when the coupling procedure described above is performed, it is done in pseudo timesteps, and the simulation time remains unchanged.

The procedure is general in the sense that it is also valid for non-steady groundwater flow. Because the procedure is made directly after the UZ-computation, the SZ-flow q_G is entered explicitly into Eq. (4-8), and q_G is actually only valid if it remains unchanged for the next SZ-timestep. It is assumed that the temporal changes in the SZ-flow are small compared to the UZ-flows, and the approximation is therefore reasonable. The q_G term also include the stream/aquifer exchange for grid squares adjacent to the river, and external boundaries.

4.4 Governing Equation

The driving force for transport of water in UZ is described in MIKE SHE WM in terms of the gradient of the hydraulic head function h, which comprises a gravitational component z and a pressure component ψ:

$$h = z + \psi \tag{4-9}$$

The gravitational head at a certain point is the elevation of the point above datum (z is positive upwards). The atmospheric pressure is chosen as reference level for the pressure head component. Under unsaturated conditions the pressure head ψ is negative due to the forces of capillarity and short range adsorptive forces between the water molecules and soil matrix. These forces are responsible for the retaining of the water in the soil. Since the two types of forces are difficult to separate, they are incorporated into the same term. Although the physical phenomena creating the pressure head under unsaturated and saturated conditions are very different, the pressure head is considered as a continuous function across the water table being negative above and positive below.

For vertical flow the driving forces for the transport of water are obtained from the gradient in vertical direction z of the hydraulic head h:

$$\Delta h = \frac{\partial h}{\partial z} \tag{4-10}$$

The volumetric flux is then obtained from Darcy's law:

$$q = - K(\theta) \frac{\partial h}{\partial z} \tag{4-11}$$

where $K(\theta)$ is the unsaturated hydraulic conductivity. Assuming that the soil matrix is incompressible and the soil water has a constant density, the continuity equation will read:

$$\frac{\partial \theta}{\partial t} = - \frac{\partial q}{\partial z} - S(z) \tag{4-12}$$

where θ is the volumetric soil moisture and S is the root extraction sink term. Combining Eqs. (4-9), (4-11) and (4-12) yields the following equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta) \frac{\partial \psi}{\partial z}\right) + \frac{\partial K(\theta)}{\partial z} - S(z) \tag{4-13}$$

The dependent variables θ, and ψ in Eq. (4-13) are interrelated through the two fundamental relationships of the soil properties: 1) **the hydraulic conductivity function** $K(\theta)$ and 2) **the soil moisture retention curve** $\psi(\theta)$.

Eq. (4-13) is general in the sense that it is equally valid to both homogeneous and heterogeneous soil verticals, and there are no constraints on the hydraulic functions. By utilizing a defined relation between θ and ψ, the soil moisture retention curve $\psi(\theta)$, θ can be eliminated.

Introducing the concept of soil water capacity:

$$C = \frac{\partial \theta}{\partial \psi} \tag{4-14}$$

which is obtained as the slope on the soil moisture retention curve, then the tension based version of the governing equation obtains:

$$C \frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial \psi}{\partial z}\right) + \frac{\partial K}{\partial z} - S \tag{4-15}$$

This equation is usually referred to as Richards' equation. It may still apply when ψ becomes positive in which case the equation degenerates to LaPlace's equation.

An alternative version of the governing Eq. (4-13) can be obtained by introducing the soil water diffusivity:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D \frac{\partial \theta}{\partial z}\right) + \frac{\partial K}{\partial z} - S \tag{4-16}$$

This equation is usually termed the diffusivity form of the flow equation and is comparable with a nonlinear Fokker-Planck equation. In order to apply the diffusivity form, the medium must be uniform in order to provide a continuous variation in θ. Further, it requires that C is different from zero, which is not fulfilled under saturated conditions, where ψ varies and θ remains constant provided incompressible media.

In the MIKE SHE WM the Richards' Eq. (4-15) has therefore been adopted for the calculation of the unsaturated flow.

4.5 Hydraulic Conductivity Function

The Governing Equation for the unsaturated flow requires information about two hydraulic functions: The hydraulic conductivity function $K(\theta)$ and the soil moisture retention curve $\psi(\theta)$ are important.

The hydraulic conductivity decreases strongly as the moisture content θ decreases from saturation (see Figure 4-2). This is not surprising since the total cross-sectional area for the flow decreases as the pores are getting filled with air. In addition hereto, when smaller part of the pore system is available to carry the flow, the path of flow becomes more tortuous. Other reasons may explain the strong decrease, e.g. an increase of the viscosity of the water, when the short range adsorptive forces become dominant in relation to the capillary forces.

The experimental procedure for measuring the K-θ function is rather difficult and not very reliable. Alternatively procedures have been suggested to derive the function from more easily measurable characterizing properties of the soil or simply to rely on empirical relationships.

Reviews of various methods for predicting the conductivity function can be found in the literature.

In the MIKE SHE WM the hydraulic conductivity K is described as a function of the effective saturation S_e:

$$K_{(E)} = K_{sat} \; S_e^n \tag{4-17}$$

where

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \tag{4-18}$$

in which θ_s, θ and θ_r are saturated, actual and residual moisture contents, respectively.

The full knowledge about the hydraulic conductivity function is seldom available, and the parameter n has to be estimated by calibration.

As a guideline the exponent n is usually small for sandy soils (2-5) and large for clayey soils (10-20). It is important to note that the value of the exponent n will influence the percolation rate in the soil and thereby influence the actual evaporation rate.

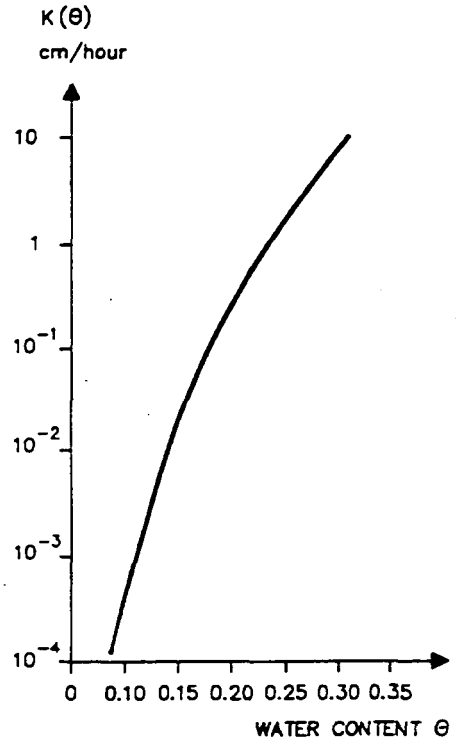

Figure 4-2 Example of the shape of the hydraulic conductivity function.

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4.6 Initial Conditions

The initial condition should be specified by the user (see **MIKE SHE WM User Guide**). There are two options available:

1) An equilibrium soil moisture/pressure profile is calculated automatically in the programme assuming that the flow is zero.

2) The soil moisture content is specified by the user as input in all computational models.

In option 1) the equilibrium profile is calculated as illustrated in Figure 4-3 assuming hydrostatic conditions. The pressure decreases linearly from zero at the groundwater table to ψ_{FC}. It is assumed that the flow is (almost) zero at moisture contents below field capacity.

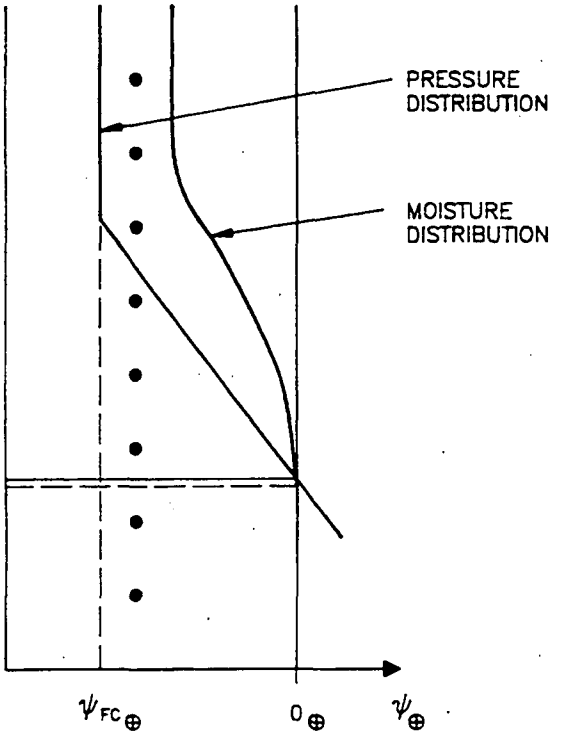

Figure 4-3 *Illustration of initial soil moisture profile and pressure head profile.*

4.7 Lumped UZ Calculation

UZ calculations should take place in every grid square in the grid system. For models including many grid squares the UZ component becomes by far the most time consuming of the components in MIKE SHE WM. Solving Richards' equation in every grid square is therefore quite expensive and time demanding when simulating long time series without some sort of approximations.

A suitable approximation which has been introduced in the UZ-component is that the UZ-calculations are only made only in a number of selected grid squares and the boundary conditions from these are transferred to equivalent grid squares. This approach is based on

the fact that if two grid squares are identical, which means they have identical 1) soil- and vegetation characteristics, and 2) identical boundary conditions, they produce the same results, and the calculations need only to be made in one of the grid squares.

The first mentioned condition, of identical soil and vegetation characteristics, is usually no serious restriction, because several homogeneous areas can usually be identified within a catchment. The second condition, however, is much more restrictive. The fluctuations in the groundwater table vary usually from grid square to grid square, and spatial variations in the rainfall and the topographic variations causes also spatial variation on the surface flow as well.

If "homogeneous" areas can be defined based on the following five characteristics:

- Topography
- Meteorological input
- Vegetation type
- Soil type
- Bypass characteristics

a representative grid square can be selected and used for the UZ-calculations. The boundary conditions i.e. infiltration rate, evapotranspiration loss and groundwater recharge, are then transferred to the other grid squares within the homogeneous group. This approximation does not introduce any water balance error, but might influence the dynamic of the simulation. However, an intelligent selection of groups of grid squares will reduce this problem considerably. In the data preparation, cf. the **MIKE SHE WM User Guide**, an initial selection of homogeneous groups can be made on basis of the depth to the groundwater table and the information of soil, vegetation and climate.

It is advisable to regroup the columns in the beginning of the calibration phase until the groundwater regime is reasonably calibrated.

When grouping the columns by choosing intervals of UZ depths it is important to select small intervals for short distances to the groundwater table.

4.8 Macropore Flow

Flow through macropores in the soil is important for many soil types. In MIKE SHE WM a simple empirical function is used to describe this process. The infiltration water divided into two parts: one part which flows through the soil matrix and one part which is routed directly to the groundwater table (bypass flow).

The bypass quantity is calculated as

$$Q_{bypass} = P_N \; P_{ratio} \sqrt{\alpha\beta} / \Delta t \qquad (4\text{-}19)$$

where P_N is the net rainfall rate, P_{ratio} is the maximum ratio of the net rainfall which can bypass the matric (under wet conditions), α, β are variables between 0 and 1 reducing the total bypass ratio under dry conditions.

It is assumed that under dry conditions (e.g. soil moisture content below field capacity) the bypass is reduced linearly from the maximum percentage to zero at e.g. wilting point. This assumption is based on the observations that macro pore flow is initiated only in connection with local ponding (saturation) at the ground surface. α and β depend on the actual soil moisture in 10 cm and 50 cm depths respectively as illustrated in Figure 4-4.

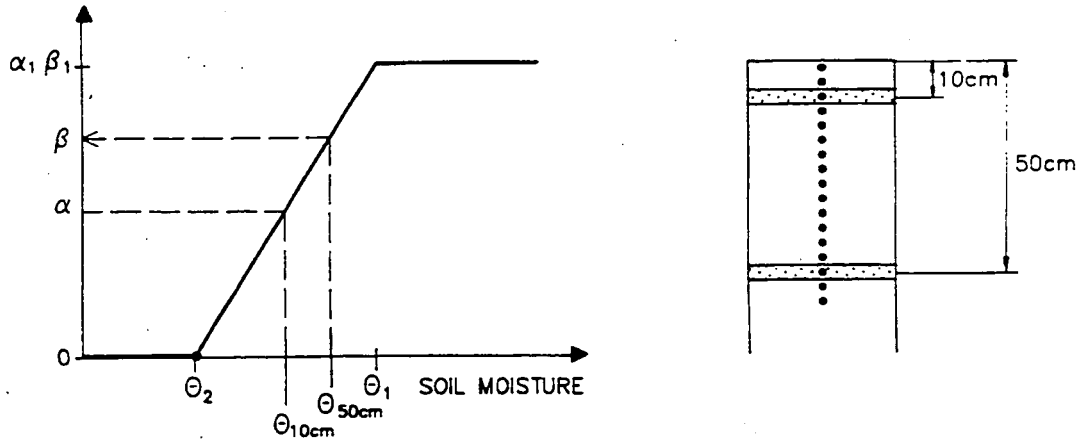

Figure 4-4 α, β as a function of the soil moisture content in 10 cm and 50 cm depth, respectively.

4.9 Sink and Sources

The governing equation (see **Governing Equation**) includes a sink/sources term (unit s^{-1}) in each computational mode.

The only type of sink/source presently used is a sink term $S_{(z)}$ describing the water extraction by roots and soil evaporation from the soil. The calculation of the sink $S_{(z)}$ is described in the **Evapotranspiration and Interception Component**.

4.10 Soil Moisture Retention Curve

The relationship between the water content θ and pressure head ψ is termed the soil moisture retention curve or the soil moisture characteristics. The function is basically defined by the textural and the structural composition of the soil. Also the organic matter content may have an influence on the relationship. A characteristic feature of the soil moisture retention curve is that ψ decreases fairly rapidly with moisture content. (See Figure 4-5). Hysteresis effects may appear, and, instead of being a single valued relationship, the θ-ψ relation consists of a family of curves. The actual curve will be determined by the history of wetting and drying of the soil.

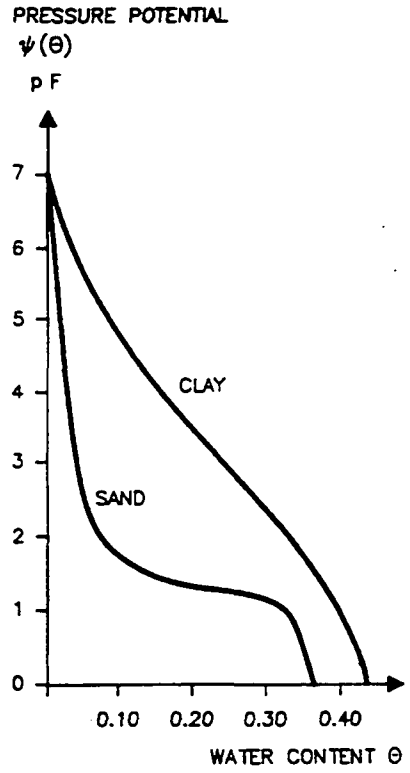

Figure 4-5 Examples of soil retention curves.

The MIKE SHE WM allows for any shape of a single-valued retention curve, and does not take hysteresis into account. A table of θ-ψ values is required and intermediate values are then calculated, using a cubic spline method, and tabulated initially in the code.

4.11 Solution Scheme

MIKE SHE WM uses a fully implicit formulation in which the space derivatives of the governing Eq. (4-20) are described by their finite difference analogues at time level n+1. The values of C(θ) and K(θ) are referred to at time level n+½. These are evaluated in an iterative procedure averaging C^n, K^n with C^m, K^m respectively. C^m and K^m are calculated in a running averaging of the coefficients found in each iteration.

This solution technique has been found to eliminate any stability and convergence problem arising from the non-linearity of the soil properties.

For an interior node, the implicit scheme yields the following discrete formulation of the vertical flow:

$$q_{J+\frac{1}{2}}^{n+1} = - K_{J+\frac{1}{2}}^{n+\frac{1}{2}} \left(\frac{\psi_{J+1}^{n+1} - \psi_J^{n+1}}{\Delta Z_{J+1}} + 1 \right) \qquad (4\text{-}20)$$

where the subscript J refers to the spatial increment and the subscript n refers to the time increment. The vertical grid system for a soil column is shown in Figure 4-6. Similar to Eq. (4-20) the discrete form of Eq. (4-9) in **Governing Equations**

$$C_J^{n+1}\,\frac{\psi_J^{n+1} - \psi_J^{n}}{\Delta t} = \left|K_{J+\frac{1}{2}}^{n+\frac{1}{2}}\left(\frac{\psi_{J+1}^{n+1} - \psi_J^{n+1}}{\Delta Z_{J+1}}\right)\right. \qquad (4\text{-}21)$$

$$\left. - K_{J-\frac{1}{2}}^{n+\frac{1}{2}}\left(\frac{\psi_J^{n+1} - \psi_{J-1}^{n+1}}{\Delta Z_J}\right)\right| \frac{1}{\frac{1}{2}\left(\Delta Z_{J+1} + \Delta Z_J\right)}$$

$$- S_J^{n+1}$$

The soil property K is centred in space by using the arithmetic mean:

$$K_{J+\frac{1}{2}}^{n+\frac{1}{2}} = \frac{K_{J+1}^{n+\frac{1}{2}} + K_J^{n+\frac{1}{2}}}{2} \qquad K_{J-\frac{1}{2}}^{n+\frac{1}{2}} = \frac{K_J^{n+\frac{1}{2}} + K_{J-1}^{n+\frac{1}{2}}}{2}$$

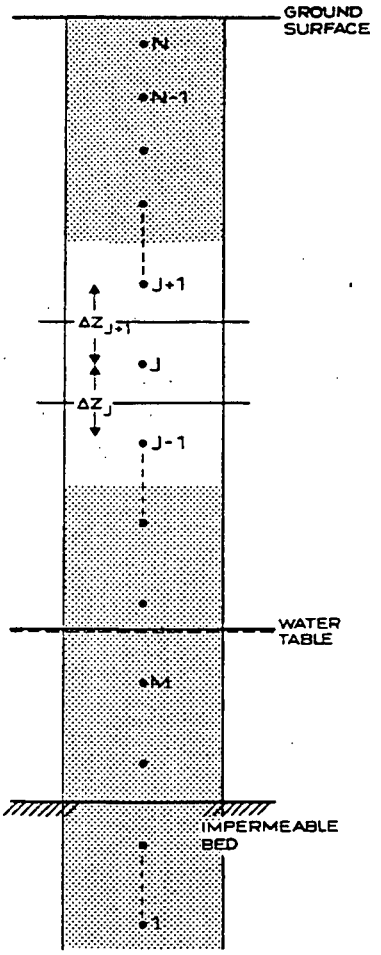

Figure 4-6 Vertical Discretization in the Unsaturated Zone.

Eq. (4-21) involves three unknown values at time n+1 and one known value at time n for each node. Written for all nodes with reference to Figure 4-6 a system of N-M+1 Equations with N-M+1 unknown is obtained. The system of Equations forms a tridiagonal matrix:

$$\begin{bmatrix} B_N & A_N & . & . & . & . & . & . & . \\ G_{N-1} & B_{N-1} & A_{N-1} & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & G_J & B_J & A_J & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & G_{M+1} & B_{M+1} & A_{M+1} \\ . & . & . & . & . & . & . & G_M & B_M \end{bmatrix} \cdot \begin{bmatrix} \psi_N \\ \psi_{N-1} \\ . \\ . \\ \psi_J \\ . \\ . \\ \psi_{M+1} \\ \psi_M \end{bmatrix} = \begin{bmatrix} D_N \\ D_{N-1} \\ . \\ . \\ D_J \\ . \\ . \\ D_{M+1} \\ D_M \end{bmatrix} \quad (4\text{-}22)$$

The J'te row in the matrix is:

$$A_J^{n+1}\ \psi_{J-1} + B_J^{n+1}\ \psi_J + G_J^{n+1}\ \psi_{J+1} = D_J \quad (4\text{-}23)$$

where

$$A_J = -\ K_{J-\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_-$$

$$B_J = C_J^{n+\frac{1}{2}} / \Delta t + K_{J+\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_+ + K_{J-\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_-$$

$$G_J = -\ K_{J+\frac{1}{2}}^{n+\frac{1}{2}} / \Delta Z_+ \quad (4\text{-}24)$$

$$D_J = C_J^{n+\frac{1}{2}}\ \psi_J^n / \Delta t + \frac{K_{J+\frac{1}{2}}^{n+\frac{1}{2}} - K_{J-\frac{1}{2}}^{n+\frac{1}{2}}}{\frac{1}{2}\left(\Delta Z_{J+1} + \Delta Z_J\right)} - S_J^{n+1}$$

$$\Delta Z_+ = \tfrac{1}{2}\,\Delta Z_{J-1}\left(\Delta Z_{J+1} + \Delta Z_J\right),$$

$$\Delta Z_- = \tfrac{1}{2}\,\Delta Z_J\left(\Delta Z_{J+1} + \Delta Z_J\right)$$

The solution to the matrix system Eq. (4-22) is solved by Gaussian elimination. Assuming that ψ_J^{n+1} and ψ_{J+1}^{n+1} can be related in the following recurrence relation

$$\psi_J^{n+1} = E_{J+1}\ \psi_{J+1}^{n+1} + F_{J+1} \quad (4\text{-}25)$$

The E_{J+1} and F_{J+1} can be calculated by combining Eqs. (4-23) and (4-25) as follows:

$$E_{J+1} = \frac{-G_J}{A_J E_J + B_J} \qquad F_{J+1} = \frac{D_J - A_J F_J}{A_J E_J + B_J} \quad (4\text{-}26)$$

Given the boundary conditions for the bottom and top nodes, the ψ_J^{n+1} is computed for all nodes in a double sweep procedure.

All E and F values are calculated from Eqs. (4-24) and (4-26) from bottom-to-top in a E, F-sweep. The ψ values are then calculated from Eq. (4-25) in a top-to-bottom sweep.

The iterative procedure applied in the numerical procedure within each timestep is shortly as follows:

a) initial estimates of C_J^o and K_J^o for the first iteration are obtained from the final result at time level n, e.g. = C_J^n and = K_J^n.

b) if the solution after the i'te iteration, for all nodes, yields

$$abs\left(\psi^i - \psi^{i-1}\right) \prec tolerance\ criteria\ for\ |\psi| \prec 0.5$$

$$abs\left(\frac{\psi^i - \psi^{i-1}}{\psi^i}\right) \prec tolerance\ criteria\ else \qquad (4\text{-}27)$$

a solution at time level n+1 has been found. If the criteria is not fulfilled the C_J^i and K_J^i are updated for the next iteration by the following relation:

$$C_J^{i+1} = \tfrac{1}{2}\left(\sum_{m=1}^{i} C_J^m / i + C_J^o\right) \qquad (4\text{-}28a)$$

$$K_J^{i+1} = \tfrac{1}{2}\left(\sum_{m=1}^{i} K_J^m / i\ K_J^o\right) \qquad (4\text{-}28b)$$

4.12 Spatial Resolution

The finite difference method used to solve the governing equation (see Solution Scheme) assumes that the soil profiles are divided into a number of discrete computational nodes in which the dependent variable is calculated. The non linearity of the process creates large gradients in soil pressure and soil moisture content during the infiltration process. It is therefore important to select appropriate node increments, which can describe the process with sufficient accuracy. However, it should be remembered that a fine spatial resolution requires large computation times, which may be a constraint in catchment simulations.

Simulation of the Hortonian type of ponding at the ground surface (high rainfall intensities on dry low permeable soils) requires a fine spatial resolution in the upper part of the profile (see Figure 4-7). Deeper in the profile the gradients are smaller and large node increments can usually be selected.
As a general guideline, one should chose a spatial resolution in the top nodes.

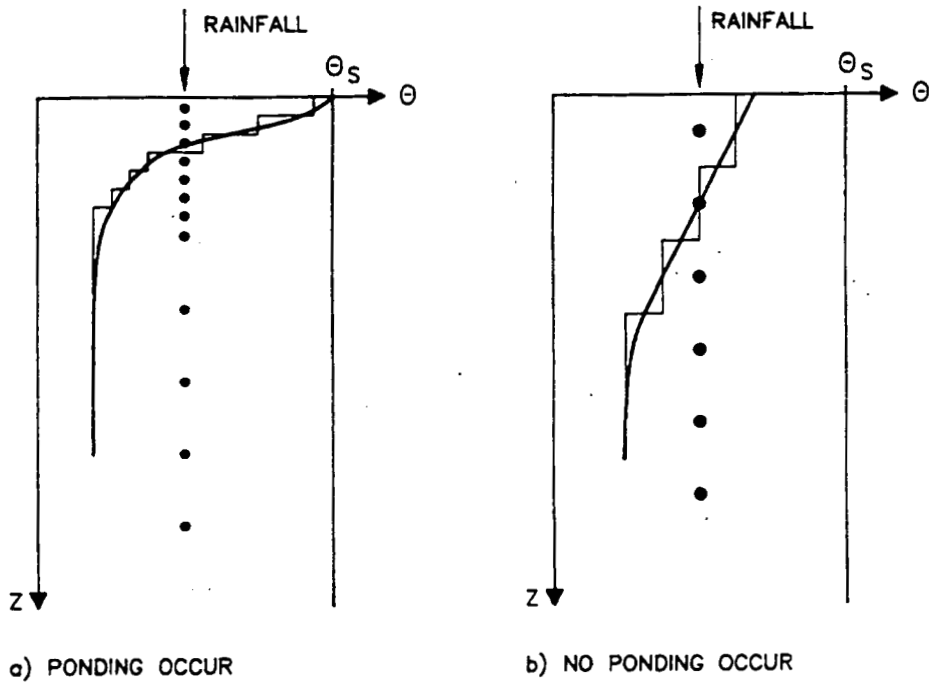

Figure 4-7 Examples of different increments in the soil profile and the resulting water content distribution of 1-3 cm for detailed studies and 3-5 cm for catchment studies. Further down in the profile larger increments can be chosen ranging from 10 cm to 30 cm.

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5 Saturated Zone Component

5.1 A General Description

The Saturated Zone (SZ) component of MIKE SHE WM calculates the saturated subsurface flow in the catchment. MIKE SHE allows for a fully three-dimensional flow in a heterogeneous aquifer with shifting conditions between unconfined and confined conditions.

The spatial and temporal variations of the dependent variable (the hydraulic head) is described mathematically by the non-linear Boussinesq equation and solved numerically by an iterative finite difference technique.

MIKE SHE gives the opportunity to chose between two groundwater modules - the SOR groundwater module based on a successive over-relaxation solution technique and the PCG groundwater module based on a preconditioned conjugate gradient solution technique. The formulation of potential flow and sink/source terms differs between the two modules to some extent.

The Saturated Zone Component interacts with the other components of MIKE SHE WM mainly by using the boundary flows from other components implicitly or explicitly as source/sinks in the Governing Equation.

5.2 Governing equations and numerical formulation

The governing flow equations for three-dimensional saturated flow in saturated porous media are:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S\frac{\partial h}{\partial t} \qquad (5\text{-}1)$$

where

K_{xx},K_{yy},K_{zz}	Hydraulic conductivity along the x,y,z axes which are assumed to be parallel to the major axes of hydraulic conductivity.
h	Piezometric head.
Q	Volumetric flux per unit volume representing source/sink terms.

S_s Specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

Two special features of this apparently straightforward elliptic equation should be noted. Firstly the equations are non-linear in the case of unconfined flow due to the presence of a free groundwater table. Secondly the storage coefficient is not a constant but will switch between two values, one for confined flow and another for unconfined. Thus abrupt changes of two orders of magnitude can be expected in this parameter.

The finite difference approximation based on a water balance for a grid block (finite volume) leads to a set of algebraic equations.

$$q_{p,i-½} + q_{p,i+½} + q_{p,j-½} + q_{p,j+½} + q_{p,k-½} + q_{p,k+½} - q_{out} = \frac{\Delta w}{\Delta t} \qquad (5\text{-}2)$$

where

q_p potential flow into cell i,j,k
q_{out} outflow from cell
Δw storage capacity

The finite-difference equation consist of potential terms, sink/source terms and storage terms. These terms are discussed in detail below.

5.3 The SOR Groundwater Module

5.3.1 Numerical formulation

The governing partial differential equation (see **Governing Equations**) is solved by approximating it to a set of finite difference equations.

These equations are developed directly by applying Darcy's law in combination with the mass balance equation for each computational node.

Considering a node i inside the model area, the total inflow $\sum Q_{ij}^{n+1}$ from neighbouring nodes and/or source/sinks between time n and time n+1 is given by:

$$\sum Q_{ij}^{n+1} = \sum q_z^{n+1} + \sum q_x^{n+1} + RH_i \Delta x^2 \qquad (5\text{-}3)$$

where q_z^{n+1} is the volumetric flow in vertical direction, q_x^{n+1} is the volumetric flow in horizontal directions, R is the volumetric flow rate per unit volume (source/sink), Δx is the spatial resolution in the horizontal directions (squares) and H_i is the saturated depth (or layer thickness) in node i. All flow terms are per unit time. The flow components are given by:

$$q_x^{n+1} = C_{ij} \Delta h^{n+1} \quad (5\text{-}4)$$

$$q_z^{n+1} = K_{ij} \Delta x^2 \Delta h^{n+1} / (\Delta z_i + \Delta z_j) \quad (5\text{-}5)$$

where C_{ij} is the conductance between nodes i and any of the adjacent nodes j in the horizontal directions, K_{ij} is the average vertical hydraulic conductivity and Δz is the node distance between nodes i and j.

The SOR groundwater module distinguish between conditions where the hydraulic conductivity of layer i (K_i) is greater or less than the hydraulic conductivity of layer j (K_j).

In the different cases K_{ij} and Δh are calculated in different ways:

$K_i<K_j$:

$\Delta h = h_i - h_j$

Layer i **and** j are confined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{\Delta z_j}{K_j}} \quad (5\text{-}6)$$

Layer i **and** j are unconfined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{h_j - z_j}{K_j} + \frac{z_j - h_i}{K_i}} \quad (5\text{-}7)$$

Layer i unconfined, layer j confined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{\Delta z_j}{K_j} + \frac{z_j - h_i}{K_i}} \quad (5\text{-}8)$$

Layer i confined, layer j unconfined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{h_j - z_j}{K_j}} \quad (5\text{-}9)$$

$K_i > K_j$:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{\Delta z_j}{K_j}} \qquad (5\text{-}10)$$

$\Delta h = h_i - h_j$

Layer i **and** j are unconfined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{h_j - z_j}{K_j}} \qquad (5\text{-}11)$$

$\Delta h = z_j - h_j$

Layer i confined, layer j unconfined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{h_j - z_j}{K_j}} \qquad (5\text{-}12)$$

$\Delta h = h_i - h_j$

Layer i unconfined, layer j confined:

$$K_{ij} = \frac{\Delta z_i + \Delta z_j}{\frac{\Delta z_j}{K_j}} \qquad (5\text{-}13)$$

$\Delta h = z_j - h_j$

The horizontal conductance is derived from the harmonic mean of the conductivity and the geometric mean of the layer thickness.

$$CI_{i-\frac{1}{2}} = \frac{K_i \; K_j \; (\Delta z_i + \Delta z_j)}{(K_i + K_j)} \qquad (5\text{-}14)$$

where

K	hydraulic conductivity
Δz	saturated layer thickness

The transient flow equation yields the following finite difference expression:

$$S \frac{h_i^{n+1} - h_i^n}{\Delta t} = \sum Q_{ij}^{n+1} \qquad (5\text{-}15)$$

where S is the storage coefficient and Δt is the timestep. Eq. (5-15) is written for all internal nodes N yielding a linear matrix system of N equations with N unknowns. The matrix is solved iteratively using a modified Gauss Seidel method, Thomas (1973).

The sequence of calculations for each grid square in the model area is illustrated in

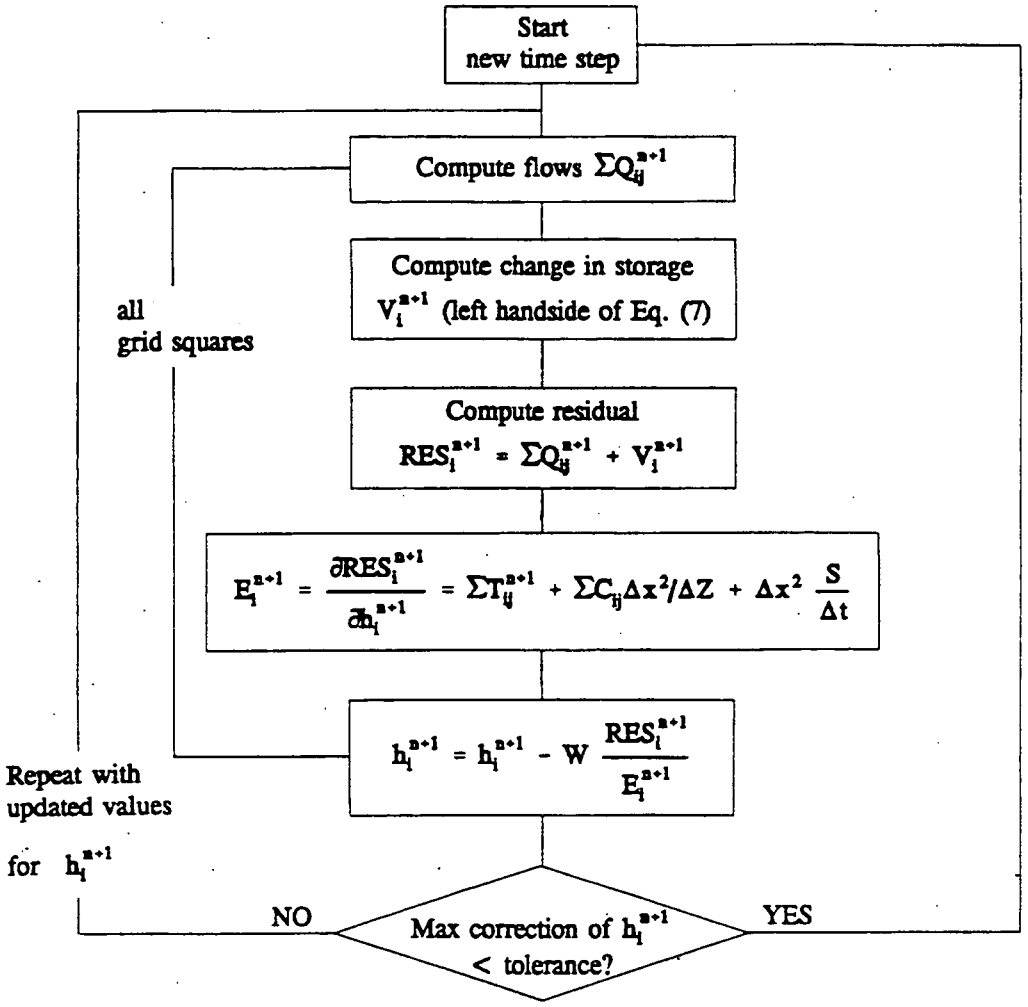

Figure 5-3, where w is a relaxation coefficient to optimize the computations. An optimal value of w is determined empirically as described in section **Relaxation Coefficient**.

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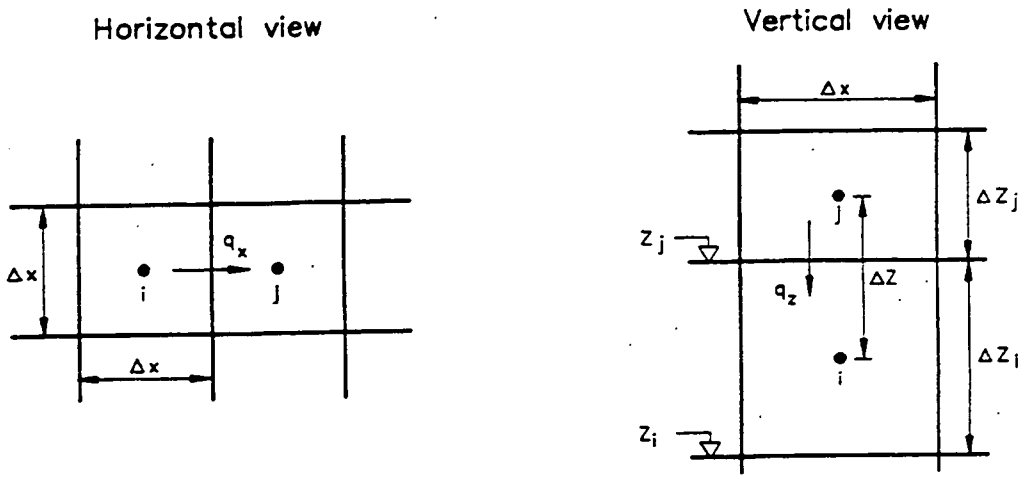

Figure 5-1 *Spatial discretization*

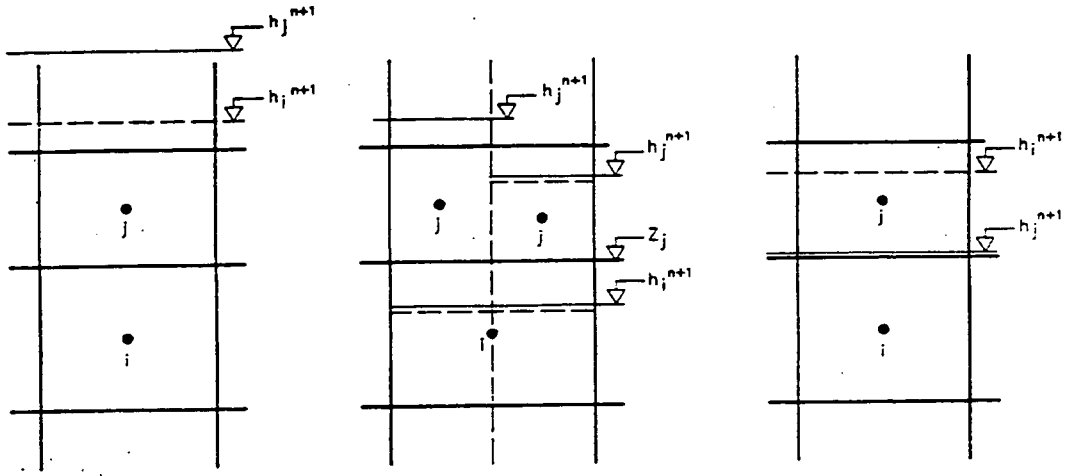

Figure 5-2 *Types of vertical flow condition, a) confined conditions in nodes i and j, b) unconfined condition in node i, c) unconfined in nodes i and j, d) dry conditions in node j and confined conditions in node i.*

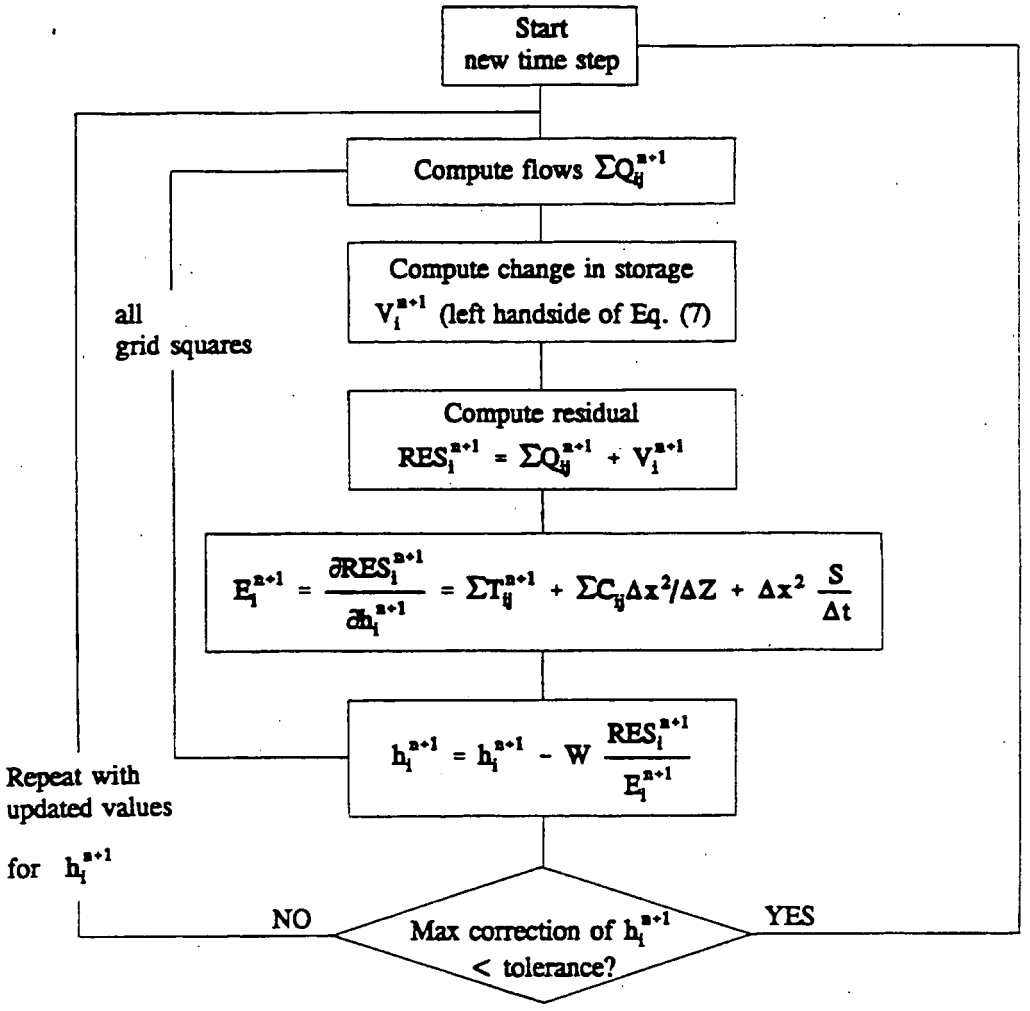

Figure 5-3 Flow chart of iteration scheme

5.3.2 Sink and source terms

The governing three-dimensional equation for flow of water (see **Governing Equation**) includes sources/sinks described as the volumetric flow rate R per unit volume. Sources/sinks includes a number of different physical processes which can be described explicitly in the flow equation:

Pumping

The user can specify ground water abstraction from any computational node inside the model area. This is done in the input data file for the **MIKE SHE Setup Program.** Time-varying ground water abstraction is specified at a point or along a line and for a computational layer. The programme allows pumping as long as the ground water head exceeds the drying conditions.

Drainage

The MIKE SHE allows for flow through drains in the soil. Drainage flow occurs only in the toplayer of the ground water model when the water table is above the position of the drains (see Figure 5-4). In MIKE SHE the drainage system is conceptually modelled as one 'big' drain within a grid square. The outflow depends on the height of the water table above the drain and a specified time constant, and is computed as a linear reservoir. The time constant characterizes the density of the drainage system and the permeability conditions around the drains.

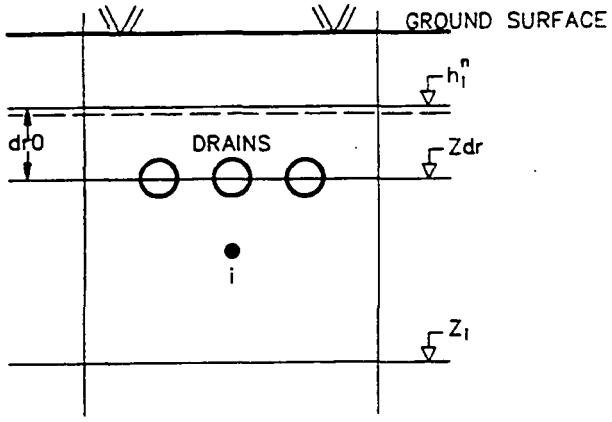

Figure 5-4 *Schematic presentation of drains in the drainage flow computations.*

The new water table position after a timestep is calculated from the flow balance equation:

$$\Delta S = (Qdr + \Sigma q)\Delta t \qquad (5\text{-}16)$$

where ΔS is the storage change as a result of a drop in the water table, Qdr is the outflow through the drain and Σq are all other flow terms in a computational node in the top layer (i.e. net outflow to neighbouring nodes, recharge, evapotranspiration, pumping and exchange to the river etc.).

The change in storage per unit area can also be calculated as:

$$\Delta S = (dr0 - dr1)S_y \qquad (5\text{-}17)$$

where dr0 is the depth of water above the drains at the beginning of the timestep, dr1 is the corresponding depth at the end of the timestep and S_y is the specific yield.

Qdr is calculated as:

$$Qdr = Cdr\ (dr0 + dr1) / 2 \qquad (5\text{-}18)$$

where Cdr is the time constant (e.g. per day). The new water depth dr1 at the end of a timestep is calculated as:

$$dr1 = \left[dr0\left(S_y - Cdr\,\Delta t / 2\right) - \sum q\Delta t\right] / \left(S_y + Cdr\,\Delta t / 2\right) \qquad (5\text{-}19)$$

The new water table elevation is:

$$hdr1 = Zdr + dr1 \qquad (5\text{-}20)$$

where Zdr is the elevation of the drains.

The drainage outflow is included in the governing equation for the ground water flow as a sink term using the hydraulic head explicitly. The computations for drainage flow use the same timestep as the timestep of the UZ calculations and may therefore be smaller than the SZ timestep. The initial drainage depth dr0 is at the beginning of an SZ timestep set equal to h - Zdr, where h is the water table elevation at time n. dr0 is adjusted during the sequence of smaller time steps so a successive lowering of the water table and the outflow takes place during an SZ timestep. This approach overcomes in some cases numerical problems if too large time steps are selected by the user. If the drainage depth becomes zero during the calculations drainage flow stops until the water table again rises above the drain elevation.

The drainage option may not only be used to simulate flow through drainpipes, but also in a conceptual mode to simulate runoff hydrographs. Due to scale problems, which usually exist in connection with regional modelling, the drainage option can be used to simulate the intermediate hydrograph response (usually called interflow). The drainage flow may also be used to simulate relatively fast surface runoff for cases where the space resolution of the individual grid squares is too large to represent small scale variations in the topography.

MIKE SHE gives opportunity for routing drainage water to local depressions, rivers or model boundaries. See MIKE SHE User Guide for further details about routing of drainage water.

Exchange to river

Exchange to the river calculated for all grid squares adjacent to a river link (see **River/Aquifer Exchange Component**)

Exchange to overland(SZ-OL exchange)

The recharge/discharge to the surface water is depended on the components included in the simulation. The saturated zone component calculate the surface recharge/discharge in point with no unsaturated zone, that is if the unsaturated zone component is excluded or the piezometric head is above surface level.

The exchange between SZ and OL is carried out implicitly by constantly updating the overland water depth.

The exchange flow is in this case of reduced OL-SZ contact calculated by use of the Darcy equation.

$$Q = \Delta h \, dx^2 / K_{leak} \qquad (5\text{-}21)$$

where K_{leak} is a leakage coefficient [1/s]

Recharge

Recharge (incl. bypass via macropores) or capillary rise from or to the soil zone. The computation of the flow exchange across the groundwater table is described in **Unsaturated Zone Component under Coupling with Ground Water Zone.**

Transpiration

Transpiration, which occurs in cases where the ground water table is within the root zone. The total potential evapotranspiration for all root zone nodes below the ground water table constitutes the sink via transpiration.

5.3.3 Relaxation Coefficient

The relaxation coefficient w is used in the solution scheme to amplify the change in the dependent variable (hydraulic head h) during the iteration (see Section 5.3.1). The value of w should be < 2 to ensure convergence but larger than 1 in order to accelerate the convergence (w is therefore often referred to as the over-relaxation coefficient). It is a complex function of the geometry of the grid and aquifer properties.

The optimal value of w is the value for which the minimum number of iterations is required to obtain the desired tolerance and can be obtained either by trial and error or by a mathematical expression (see e.g. Marsily, 1986). Figure 5-5 illustrates the relation between w and the number of iterations for a given grid.

In practice the optimal value of w can easily be found after setting up the grid. The model is run for a few time steps (e.g. ten) with a range of w values between 1 and 2, and the total number of iterations is plotted for each run against the w value as shown in Figure 5-5. The minimum number of iterations corresponds to the optimal value of w.

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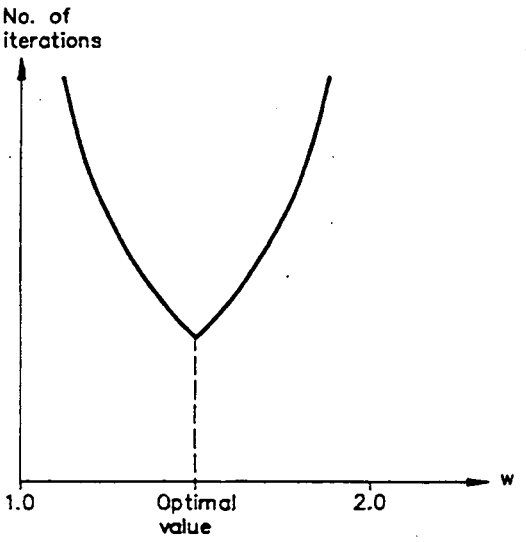

Figure 5-5 *Empirically relationship between the relaxation coefficient w and number of iterations for a given model.*

5.3.4 Steady State Solution

Steady state conditions can be reached by running a number of time steps with constant boundary conditions until the changes in the dependent variable has reached an acceptable level.

5.4 The PCG Groundwater Module

5.4.1 Potential terms

The potential flow is calculated using Darcy's law

$$Q = \Delta h C \tag{5-22}$$

where Δh is the pressure difference and C is the conductance.

Conductance

The horizontal conductance is derived from the harmonic mean of the conductivity and the geometric mean of the layer thickness.

$$CI_{i-\frac{1}{2}} = \frac{K_{i-1,j,k} \; K_{i,j,k} \; (\Delta z_{i-1,j,k} + \Delta z_{i,j,k})}{(K_{i-1,j,k} + K_{i,j,k})} \tag{5-23}$$

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where

K hydraulic conductivity
Δz saturated layer thickness

The vertical conductance between two cells is computed as a weighted serial connection of the hydraulic conductivity. The conductance always is calculated from the middle of layer k to the middle of the layer k+1.

$$CK = \frac{\Delta x^2}{\frac{\Delta z_k}{2K_{z,k}} + \frac{\Delta z_{k+1}}{2K_{z,k+1}}} \qquad (5\text{-}24)$$

where Δz is the layer thickness
Pressure difference
Under confined conditions the pressure difference is simply the pressure difference between the corresponding nodes. A special case appear when unconfined cells are present.

Dewatering conditions in cell k+1
Consider the situation in Figure 5-6

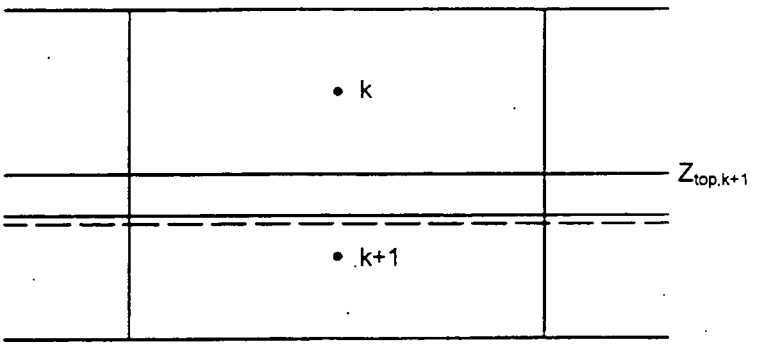

Figure 5-6 Dewatering conditions in cell k+1.

The actual flow between cell k and $k+1$ is

$$q_{k+½} = CK_{k+½}\left(z_{top,k+1} - h_k\right) \qquad (5\text{-}25)$$

In the present solution scheme the flow will be computed as

$$q_{k+½} = CK_{k+½}\left(h_{k+1} - h_k\right) \qquad (5\text{-}26)$$

Subtracting Eqs. (5-25) from (5-26) gives the correction term

$$q_c = CK_{k+½}\left(h_{k+1} - z_{top,k+1}\right) \qquad (5\text{-}27)$$

This correction term is added to the right side of the finite difference equation using the last computed head

Dewatering conditions in cell k

A correction must also be applied to the finite difference equation for the dewatering cell itself. Consider Figure 5-7

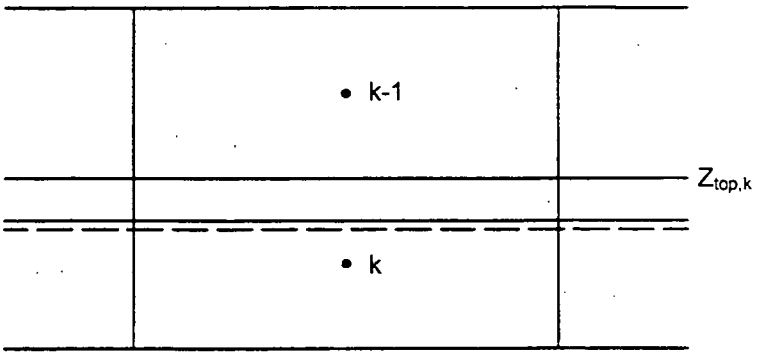

Figure 5-7 Dewatering conditions in cell k.

The actual flow from cell *k-1* to *k* is

$$q_{k+½} = CK_{k-½}\left(h_{k-1} - z_{top,k}\right) \tag{5-28}$$

Again the computed flow is

$$q_{k+½} = CK_{k+½}\left(h_{k-1} - h_k\right) \tag{5-29}$$

Subtraction Eqs. (5-28) from (5-29) gives the correction term

$$q_c = CK_{k-½}\left(z_{top,k} - h_k\right) \tag{5-30}$$

This correction term is added to the right side of the finite difference equation using the last computed head

5.4.2 Storage terms

The storage capacity is computed by

$$\frac{\Delta w}{\Delta t} = \frac{S2\left(h^n - z_{top}\right) + S1\left(z_{top} - h^{n-1}\right)}{\Delta t} \tag{5-31}$$

where

n	time step
S1	storage capacity at the start of the iteration at time step *n*
S2	storage capacity at iteration *M*

For confined cells the storage capacity is given as

$$S = \Delta x^2 \Delta z S_{art} \tag{5-32}$$

and for unconfined cells the storage capacity is given as

$$S = \Delta x^2 S_{free} \qquad (5\text{-}33)$$

Source/sink terms

The sink and source terms includes all exchange terms between the groundwater zone and the surroundings:

- pumping
- exchange to river
- exchange to overland
- recharge
- transpiration
- drainage

Pumping

The user can specify ground water abstraction from any computational node inside the model area. (see **MIKE SHE WM User Guide**). Time-varying ground water abstraction is specified at a point or along a line in a computational layer. The programme allows pumping as long as the ground water head exceeds bottom of the computational layer.

Exchange to river

The river/aquifer exchange is calculated for all grid squares adjacent to a river link (see **River/Aquifer Exchange Component)**

Exchange to overland (SZ-OL exchange)

The recharge/discharge to the surface water is depended on the components included in the simulation. The saturated zone component calculate the surface recharge/discharge in point with no unsaturated zone, that is if the unsaturated zone component is excluded or the piezometric head is above surface level.

The exchange between SZ and OL is carried out implicitly by constantly updating the overland water depth.

The exchange flow is calculated by use of the Darcy equation.

$$Q = \Delta h C K_{1/2}$$

where CK is the conductance from surface level to the middle of the top calculation layer

In case of full contact between overland and the saturated zone the conductance between overland and layer 1 is computed as

$$CK_{½} = \frac{\Delta x^2}{\frac{\Delta z_1}{2K_{z,1}}} \quad (5\text{-}34)$$

where

$\Delta Z1$ thickness of layer 1 [m]
$K_{z,1}$ vertical conductivity [m/s}

In areas with reduced contact between overland and the saturated zone the conductance between overland and layer 1 is computed as

$$CK_{½} = \frac{\Delta x^2}{\frac{\Delta z_1}{2K_{z,1}} + \frac{1}{K_{leak}}} \quad (5\text{-}35)$$

where

$\Delta Z1$ thickness of layer 1 [m]
$K_{z,1}$ vertical conductivity [m/s]
K_{leak} leakage coefficient [1/s]

Recharge

Recharge (incl. bypass via macropores) or capillary rise from or to the soil zone. The computation of the flow exchange across the groundwater table is described in **Unsaturated Zone Component under Coupling with Ground Water Zone**.

Transpiration

Transpiration, which occurs in cases where the ground water table is within the root zone. The total potential evapotranspiration for all root zone nodes below the ground water table constitutes the sink via transpiration.

Drainage

The MIKE SHE allows for flow through drains in the soil. Drainage flow occurs when the water table is above the position of the drains. In MIKE SHE the drainage system is conceptually modelled as one `big` drain within a grid square. The outflow depends on the height of the water table above the drain and a specified time constant, and is computed as a linear reservoir. The time constant characterises the density of the drains.

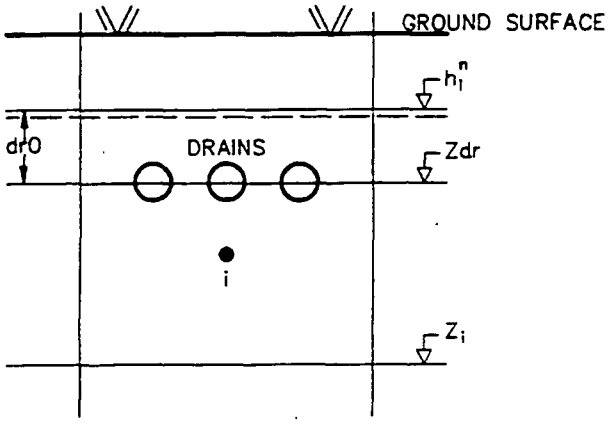

Figure 5-8 *Schematic presentation of drains in the drainage flow computations.*

The drainage flow is given as

$$q = (h_n - zdr_n)cdr_n \qquad (5\text{-}36)$$

where

h_n	head in drainage point
zdr_n	drainage level
cdr_n	drainage time constant

MIKE SHE gives opportunity for routing drainage water to local depressions, rivers or model boundaries. See MIKE SHE User Guide for further details about routing of drainage water.

5.4.3 Steady State Solution

The PCG solver provides a steady state option (See MIKE SHE User Guide). The steady state solution sets all storage coefficients equal to zero. (All specified storage coefficients are overruled)

5.5 Boundary Conditions

The SZ component allows for the three types of boundary conditions:

1. Dirichlet's conditions, where the hydraulic head is prescribed on the boundary
2. Neumann's conditions, where the normal gradient of the hydraulic head (flux) is prescribed on the boundary
3. Fourier's conditions, where the head dependent flux is prescribed on the boundary.

Prescribed head can be specified at all grid squares (at the catchment boundary as well as inside the model area) and for all computational layers. The head may be time-invariant equal to the initial head or can vary in time as specified by the user. An important option is the transfer of space- and time interpolated head boundaries from a larger model to a

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subarea model with a finer discretization. The transfer is made with the **mshe.bnd/mshe_bnd.exe** postprocessing programme (see **MIKE SHE PP User Guide**).

Prescribed gradients and fluxes can be specified in all layers at the model boundary. Presently these boundary conditions can not be time-varying. Sinks in terms of pumping rates can be specified in all internal nodes. If the unsaturated zone component is not included in a given model application, the ground water recharge can be specified apriori as a source (or sink, if netcapillary rise occur) for example as a rainfall input data file.

The flow exchange to the river system is included in the source/sink term of the governing equation and can be regarded as a boundary condition of the third type for all grid squares with 'contact' to the river system. The flow exchange rate is a function of the river water level, the river width, the elevation of the riverbed and further depends of the hydraulic properties at the riverbed and/or aquifer properties in the concerned grid square.

5.6 Initial Conditions

The initial conditions is specified as constants or T2 files (See **MIKE SHE WM User Guide**). The initial conditions in boundary cells is held constant during a simulation, i.e. the initial head in cells with Dirichlet's boundary conditions becomes the boundary head during the simulation.

5.7 Tolerance Criteria

The tolerance criteria (TOL) for the iterative solution of the flow equations is the maximal allowable value of residual error during an iteration. The solution is obtained when the residual error during an iteration in any computational node is less than the specified tolerance. The value of TOL should be selected according to aquifer properties and dimensionality of the model.

In practice the TOL value will always be a compromise between accuracy and computing time. It is recommended to check the water balance carefully with the **mshe.wbl/mshe_wbl.exe** postprocessing programme (see **MIKE SHE WM User Guide**), but it should be emphasized that large internal water balance errors between adjacent computational nodes may not be detected. If large errors in the water balance is produced the TOL should be reduced.

6 River/Aquifer Exchange Component

6.1 A General Description

A river system influences a large part of the ground water system in a catchment as it traverse the catchment in many directions. The river will usually control the ground water head in horizontal and vertical directions defining recharge and discharge areas. The surface area of the river system is , however small compared to the catchment area, and for regional modelling the river width may typically occupy a few percentage of the grid square size.

In many application the river can therefore be represented in a separate node system running along the boundaries of the grid squares acting as a line source/sink. The Exchange Component assumes that the width of the river is small compared to the grid square dimension. If this assumption is invalid the option described in the Saturated Zone Component under Boundary Conditions may be used.

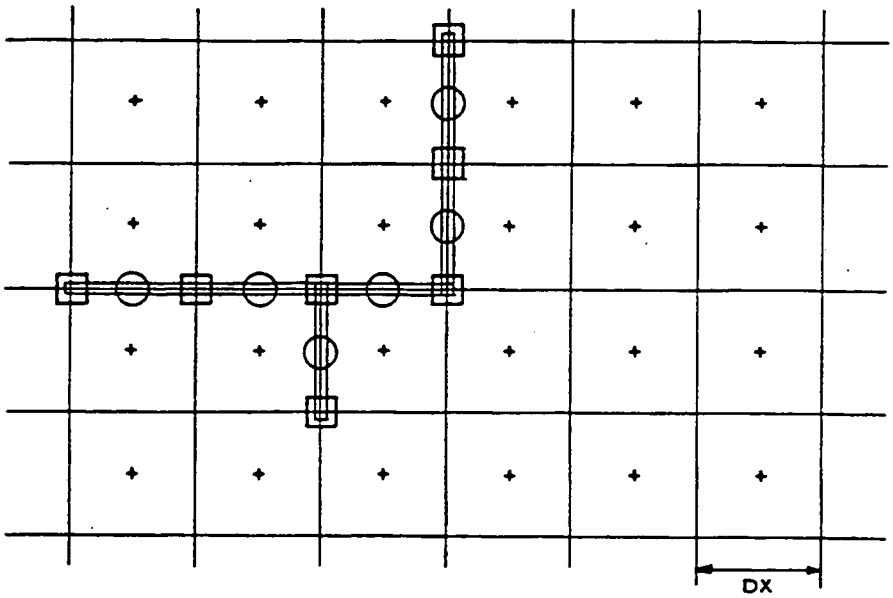
The river flow computations are carried out in the corners of the grid squares (see also the Overland Flow and Channel Flow Component). Interaction between the river and the ground water and the overland flow is assumed to take place in the middle of the intermediate river links connecting adjacent computational nodes, see Figure 6-1.

The Ex Component includes two options of the river/aquifer exchange:

- The river is in 'full' (but not necessarily fully penetrating the aquifer) contact with the ground water aquifer

- A low permeable riverbed layer separates the river from the ground water aquifer.

Under this option two descriptions can be chosen as described below.



+ Calculation node point for OCR (overland flow), UZ and SZ

  Calculation node point for OCF (river flow)

O Calculation node point for OCF interaction with OCR and SZ. I.e. an internal boundary point for overland flow and a boundary point for the SZ calculation involving either one pressure head or two groundwater discharges.

Figure 6-1 Representation of the river in the model grid square system.

6.2 Flow Equations

The ground water flow between two adjacent computational nodes in a certain computational layer is calculated assuming horizontal flow and hydrostatic pressure head distribution in the vertical direction of the computational layer.

This approximation is appropriate when dealing with ground water flow between grid squares or when the river is assumed to fully penetrate the aquifer, but less accurate if the river is only partially penetrating the aquifer. In nature vertical gradients will occur the vicinity of the river introducing an additional head loss. If the width of the river is small compared to the aquifer depth the head loss around the river will therefore be the determining factor for the flow exchange as well as for the gradient of the ground water head.

In MIKE SHE the flow exchange is calculated using Darcy's law. Two options take the additional head loss around the river bottom into account in an approximative way. In a third option the exchange flow is calculated directly from the vrtical head difference between the water level in the river and the adjacent grid square nodes.

A further important requirement to the scheme concerns the vertical discretization. If homogenous conditions exist the flow rate to the river should be independent of the

chosen vertical discretization of the aquifer. It is important to note that this does not imply that the resulting ground water heads are independent of the vertical discretization since eg. a two-dimensional description neglects the vertical head gradient in contrast to a three-dimensional description.

6.3 Low Permeable Riverbed Lining (Option One)

When the river is separated from the aquifer by a low permeable lining the flow exchange is calculated from the following equations (see Figure 6-26-2):

$$Q_{ij} = K_{ij}\overline{H}_{ij}\left(H^{*}_{ij} - h_{ij}\right) / \left(\Delta x / 2 - W / 4\right)$$

$$Q_{Exij} = W / 2n \; L_B\left(H^{*}_{ij} - H_R\right) \qquad (6\text{-}1)$$

$$Q_{Ex} = \Sigma Q_{Exij} \quad for\ i = 1,n;\ j = 1,2$$

where H_{ij}^{*} is the hydraulic head in layer i of gridsquare j beneath the riverbed lining, L_B is the leakage coefficient in the lining. Eq. (6-1) involves two equations with two unknowns H_{ij}^{*} and $\left(Q_{ij}\text{ or }Q_{Exij}\right)$ of each layer and gridsquare adjacent to the river. The flow is calculated by substituting H_{ij}^{*} in one of the above equations. H_{ij}^{*} will always lie between H_R and h_{ij}. If H_{ij}^{*} is below the riverbed the ground water table is not in contact with the river and the outflow from the river (assuming a flowing river) is calculated as:

$$Q_{Exij} = W / 2 \; C_B\left(H_R - Z_R\right) / D_B \qquad (6\text{-}2)$$

where Z_R is the riverbed elevation.

It is important to note that in Eq. (6-4) in No Riverbed Lining and in Eq. (6-1) above the vertical gradients (and thereby the vertical conductivity in the aquifer) are always taken into account in a three-dimensional model since the flow between the individual layers in a grid square adjacent to the river is calculated in the SZ solution scheme.

The inherent assumption in a two-dimensional model is that vertical gradient in the aquifer is neglected. However, the gradual increase in vertical flow area away from the river is included in the SZ solution scheme because the flow between the first and second grid square away from the river includes the entire saturated depth of the aquifer. If therefore only a local contraction is observed around the river, the user should use a sufficient detailed horizontal discretization in order to obtain a correct gradient on the simulated ground water table.

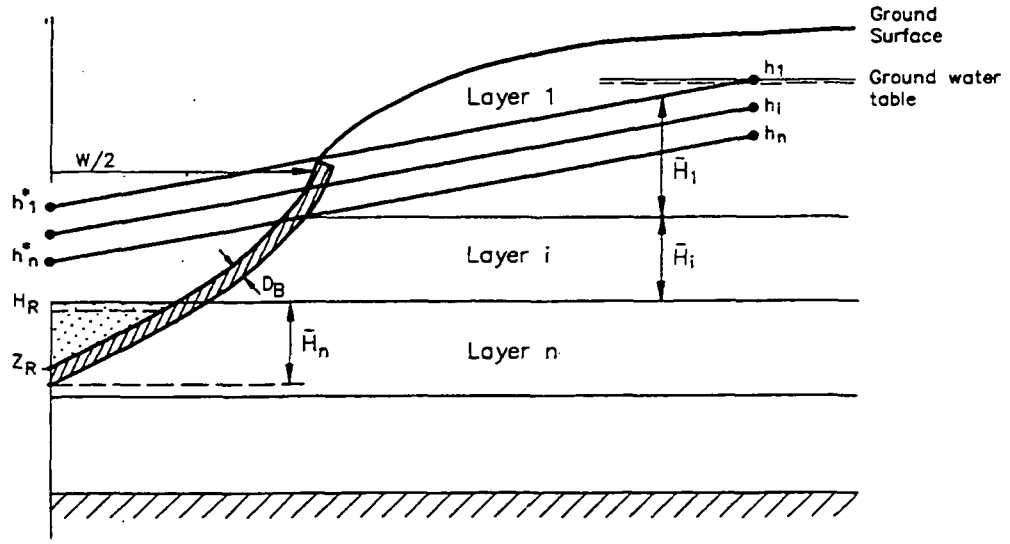


Figure 6-2 Illustration of river/aquifer exchange for a river with a low permeable lining.

6.4 Low Permeable Riverbed Lining (Option Two)

In this permeable option the flow exchange is calculated by

$$Q_{Exij} = W / 2n \; L_B(n_{ij} - H_R)$$

$$Q_{Ex} = \Sigma Q_{Exij} \quad for\ i = 1,n;\ j = 1,2 \tag{6-3}$$

neglecting the head gradient between the grid square node and the mid point below the riverbed lining.

6.5 No Riverbed Lining

In case of 'full' contact between the river and the aquifer the calculation of the flow exchange between the river and the individual computational layers is given by:

$$Q_{ij} = C_{ij} \overline{H}_{ij} \left(H_R - h_{ij}\right) / (\Delta x / 2 - W / 4)$$

$$Q_{Ex} = \Sigma Q_{ij} \quad for\ i = 1,n;\ j = 1,2 \tag{6-4}$$

where Q_{ij} is the flow exchange between river and gridsquare j in layer i, $\overline{H}_{ij}$ is the saturated thickness in layer i, H_R is water level in the river, h_{ij} is the hydraulic head in gridsquare j in layer i, C_{ij} is the hydraulic conductivity in gridsquare j in layer i, Δx is gridsquare size and W is river width at banklevel, n is the number of computational layers

penetrated by the river, Q_{Ex} is the total flow exchange to the river. For layer n, $\overline{H}_{nj}$ is the saturated thickness of layer n above the riverbed.

It appears from Eq.(6-4) that only the saturated part of the aquifer which is above the riverbed is taking part in the exchange flow assuming that the river depth is the determining factor for the flow exchange.

MIKE SHE
Water Movement Module

PART III

Appendices

Appendix A

References

References

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Appendix B

Examples

Introduction

Together with your installation of the executable programmes of MIKE SHE you will find a directory containing a number of test examples illustrating different ways of setting up a model. The examples include some simple setup's which verifies that model results are consistent with simple analytical solutions. Moreover, some model application setup's are included. These examples will guide you through a number of the facilities included in the MIKE SHE software package. The model setup's are located on subdirectories under $shedir/data/Examples and called Applications and Verification, respectively.

Model Application Examples

The basis for all the examples is a water resources study carried out at DHI. The catchment - the Karup basin - has the following characteristics:

Area: Approx. 400 km^2.

Rivers: One main river and several minor tributaries.

Aquifers: The groundwater reservoir is an unconfined sandy aquifer with some lowpermeable lenses of clay and silt. The lower impermeable boundary follows the surface of the tertiary deposits.

Soil distribution: Three main soils are represented in the area i.e. fine sands, sand/gravel and postglacial deposits (though having the same characteristics as sand/gravel);

Vegetation pattern: Four different types of vegetation have been defined in the area i.e. forest, grassland (cultivated), heath and agricultural areas with different crops;

Precipitation network: Nine precipitation areas and the corresponding time-series with daily values have been defined in the area;

Evaporation: The potential evaporation is defined from one station;

Groundwater abstraction: There is no information concerning groundwater abstraction within the catchment, but in order to show the format of time series for abstraction a data file has been produced on the TIME directory;

The QC directory contains 7 examples of a model setup with different number of components of MIKE SHE WM included. All necessary data files for establishing a model setup and for running MIKE SHE WM are located on the sub-directories. In addition, a number of useful specification files both for the utility programmes and for graphical presentation have been prepared and can be used when you go through the examples.

Not all data files containing the original digitised data are stored on the directories. For those not, only the resulting matrix data files generated with the utility programme

MSHE.OL are included (this concerns the spatial distributions of soil types (soil.T2), vegetation (veg.T2) and the base level of the aquifer (lay1L.T2)). Table 1 summarises the data files and their content.

Table 1 Parameters, raw data and data files.

"Parameter"	"Raw" data (on the directory DIGFILES)	Processed data	Remarks
Catchment	CATCHMENT.dig	MAPS/catgrid10.T2 MAPS/catgrid5.T2	The test examples have been setup in a 1000 m grid (catgrid10.T2);
River network	river.dig	MAPS/river.rdf	
Topography	TOPOGRAPHY.dig	MAPS/topography.T2	
Precipitation	PRDZONES.dig	MAPS/prd.T2 TIME/prd.T0	There are 9 precipitation stations in the catchment. The spatial distribution is of the 9 stations is described in prd.T2 while the temporal distribution is described in prd.T0;
Temperature		TIME/ted.T0	Uniform temperature;
Potential evaporation		TIME/epd.T0	Uniform potential evaporation;
Vegetation		MAPS/ved.T2 TIME/rdf.T0 TIME/lai.T0	There are 4 different vegetations in the area (1: farmland, 2: forest, 3: heath 4: grass). The spatial distribution of the vegetation is described in ved.T2 while the temporal distribution of root distribution and leaf area index are described in rdf.T0 and lai.T0, respectively;
Soil types		DBASE/karup.db1 MAPS/soil.T2	Four different soils are described in the database karup.db1. The vertical distributions of the soil types are defined in the file selection files and the spatial distributions are described in soil.T2;
Geology	DIGFILES/LEN0?.dig	MAPS/lay1L.T2 MAPS/lense?.T2 MAPS/lense?U.T2 MAPS/lense?L.T2	The aquifer is unconfined with five inhomogeneities (lenses). The lower level of the aquifer is described by lay1L.T2. The lenses are described by their horizontal boundaries by lense?.T2 and their upper and lower levels are described by lense?U.T2 and lense?L.T2, respectively;
Hydrogeology		MAPS/hszini.T2	The initial groundwater table is read from a data file which contains the calculated head from an earlier simulation.
Drainage		MAPS/drainlevel.T2 MAPS/cdr.T2	The levels of the drains are described by drainlevel.T2 and the time constants are described by cdr.T2;
Abstraction		TIME/exd.T0	An example of a time series data file for groundwater abstraction;
Sub-catchment water balance		MAPS/wbl.T2	A data file which can be input to the water balance utility program for calculating sub-catchment water balances;
River cross-sections		MAPS/crs?.crs	Examples of cross-sections defined for the River Graphical Editor;
Miscellaneous		MAPS/head DIGFILES/head	Examples of heading lines for digitised data and "T2-data";

Graphical presentation of data

Particular attention should be paid to the Graphical Presentation Tool and the specification files for it. They are divided into different directories referring either to data or to the different types of model setup. The specification file located in the directory PLOT/DATA can be loaded and plots can be made without any further work. Prepared specification files and a short description of each plot is given below:

prd.plt: shows examples to present precipitation data as daily values, accumulated values, and annually as well as monthly accumulated values;

cat+topo.plt: shows the raw digitised data of the catchment boundary and the topography;

QCtest0

The model setup called QCtest0 is a very simple setup where only the unsaturated zone (UZ) and the evapotranspiration (ET) components are included. The setup is a so-called single column test with the model area consisting of 3x3 grid squares with four boundary grids and one computational grid.

The setup can be displayed on the screen by loading the QCtest0.fsf file and entering following menus:

D.1 - preparation of the data base for parameters for the unsaturated zone;
F.1.1 - catchment definition;
F.1.7 - soil profile definition;
F.1.15 - definition of data for the 'dummy' component;

The setup is processed to produce the binary input data file QCtest0.fif, required by MIKE SHE WM, by executing the 'setup program' from menu F.3.

A number of data in the QCtest0.fif data file can be inspected using the input retrieval utility programme MSHE.IR from menu U.2. For example the soil properties in an unsaturated zone profile can be displayed by loading and executing the specification file QCtest0.ir from the MACRO directory.

The MIKE SHE WM simulation is started from menu F.4.

After the simulation has been completed the results can be graphically presented by using the following specification files located on the directory PLOT/TEST0:

uz.plt: shows a time series of the water content in the unsaturated zone together with the temporal variations in precipitation and the infiltration to the unsaturated zone;

evapo1.plt: shows time series of actual evaporation composed of evaporation from the canopy, the interception, the soil and transpiration through the plants together with other time series related to the upper part of the hydrological cycle;

The results can also be retrieved as time series of e.g. water content in the unsaturated zone and stored as an ascii file. This is done from menu U.1 by loading the specification file QCtest0.or located on the directory MACRO.

QCtest1

The model setup called QCtest1 shows an example of a two-dimensional groundwater model of the catchment area. The geological interpretation made is rather simple with only one homogeneous geological layer with uniform hydrogeological parameters.

The setup can be accessed by loading the QCtest1.fsf file and go through the following menus:

F.1.1 - catchment definition;
F.1.2 - the geological interpretation;
F.1.2.a,b - the geological layer and its hydrogeological parameters;
F.1.3 - the vertical discretisation which follows the geological layers;
F.1.4 - the initial conditions which correspond to a simulated potential head;
F.1.5 - the boundary conditions which is a no-flow condition along the entire boundary;
F.1.6 - the parameters for drainage i.e. drain level and time constant;
F.1.15 - definition of data for the 'dummy' component;

The setup can be processed to produce the binary input data file QCtest1.fif by executing the 'setup program' from menu F.3.

Some of the data files in the flow setup file have been determined from digitised data. You can e.g. see how the two-dimensional interpolation routine works in the menu U.6 by loading and executing the specification file QCtestg.topo from the MACRO directory.

The flow input file can be inspected with the input retrieval utility from menu U.2. You can for example see the drainage levels by loading and executing the specification file QCtest1.ir from the MACRO directory.

The simulation can be started from menu F.4.

After the simulation has been completed the results can be graphically presented by the following specification files located on the directory PLOT/TEST1:

cross.plt: shows three sections of the geological interpretation in the model area;

head+flow.plt: shows the simulated head and flow arrows in the groundwater zone after one month of simulation;

The results can also be retrieved as ascii files (tables). E.g. the simulated groundwater head after 5 days from menu U.1 by loading the specification file QCtest1.or located on the directory MACRO.

QCtest2

The model setup called QCtest2 is in principle the same as QCtest1, but now the components for snow melt, evapotranspiration and unsaturated flow have been added. Also the complexity of the groundwater part is increased by including five lowpermeable lenses in the geological interpretation.

The setup can be inspected by loading the QCtest2.fsf file and going through the following menus:

F.1.1 - catchment definition;
F.1.2 - the geological interpretation;
F.1.2a+b - the geological layer and its hydrogeological parameters;
F.1.3a+b - the geological lenses and their hydrogeological parameters;
F.1.3 - the vertical discretisation which follows the geological layers;
F.1.4 - the initial conditions which correspond to a simulated potential head;
F.1.5 - the boundary conditions which is a no-flow condition along the entire boundary;
F.1.6 - the parameters for drainage i.e. drain level and time constant;
F.1.7 - the vertical distribution in the soil profiles;
F.1.8 - the classification of the unsaturated zone codes and the spatial distribution of the soils;
F.1.12 - the distribution in time and space of parameters for the evapotranspiration calculations (potential evaporation, vegetation, leaf area index, root distribution and empirical parameters for the Kristensen and Jensen evaporation model;
F.1.14 - the parameters for the snow melt routine;
F.1.15 - definition of data for the 'dummy' component;

The setup can be processed to produce the binary input data file QCtest2.fif by executing the 'setup program' from menu F.3.

Some of the data files in QCtest2.fsf data file have been determined from digitised data. You can e.g. see how the grid overlay routine works in menu U.4 by loading and executing the specification file QCtestg.ol from the MACRO directory. It will establish the distribution of precipitation areas from digitised polygons.

The flow input file QCtest1.fif can be inspected using the input retrieval programme MSHE.IR from menu U.2. You can e.g. see the distribution of the grids in which unsaturated flow is executed by loading and executing the specification file QCtest2.ir from the MACRO directory.

The simulation can be started from menu F.4.

After the simulation has been completed the results can be graphically presented by the following specification files located on the directory PLOT/TEST2:

cross.plt: shows three sections of the hydraulic conductivity in the model area;

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head+flow.plt: shows the simulated head and flow arrows in the groundwater zone after one month of simulation;

The results can also be retrieved as tables with time series of e.g. the simulated head in grid point (20,20) from menu U.1 by loading the specification file QCtest2.or located on the directory MACRO.

QCtest3

The setup called QCtest3 includes only the overland flow component, i.e. assumes that the entire catchment is paved.

The setup can be inspected by loading the QCtest3.fsf file and going through the following menus:

F.1.1 - catchment definition;
F.1.10 - the river network;
F.1.11 - parameters for the overland and river flow;
F.1.15 - definition of data for the 'dummy' component;

The setup can be compiled to QCtest3.fif input file by executing the 'setup program' from menu F.3.

Some of the input data files in QCtest3.fsf input data file have been determined from digitised data. You can e.g. see how the river network has been established by activating the Graphical River Editor and load the data file river.dig which is located on the directory DIGFILES. Compare it with the processed version - river.rdf - which is located on the directory MAPS.

You can e.g. see the distribution of the detention storage (which in this case is uniform equal to 0) by loading and executing the specification file QCtest3.ir from the MACRO directory.

The simulation can be started from menu F.4.

After the simulation, the results can be graphically presented by the following specification files located on the directory PLOT/TEST3:

oc+river.plt: shows time-series of river flow and maps of water depth on the surface and in the river;

river.plt: shows the maps of the water depth in the river after 1, 2, 3 and 4 days of simulation;

topo.plt: shows compiled topographical map;

The results can also be retrieved as tables of e.g. the simulated depth of overland water after five days from menu U.1 by loading the specification file QCtest3.or located on the directory MACRO.

QCtest4

The model setup QCtest4 is in principle the same as the setup QCtest1, but the groundwater part is now more complex thus the geological interpretation now includes five lenses with a lower hydraulic conductivity than the surrounding aquifer. Furthermore, the groundwater zone has now been divided into 10 computational layers.

The setup can be investigated by loading the QCtest4.fsf file and go through the following menus:

F.1.1 - catchment definition;
F.1.2 - the geological interpretation;
F.1.2a+b - the geological layer and its hydrogeological parameters;
F.1.3a+b - the geological lenses and their hydrogeological parameters;
F.1.3 - the vertical discretisation which in this case is established with a uniform thickness of all layers;
F.1.4 - the initial conditions which correspond to a simulated potential head;
F.1.5 - the boundary conditions which is a no-flow condition along the entire boundary;
F.1.6 - the parameters for drainage i.e. drain level and time constant;
F.1.15 - definition of data for the 'dummy' component;

The QCtest4.fif input data file is generated as described above. The MIKE SHE WM simulation can be started from menu F.4.

The simulation results can be graphically presented by the following specification files located on the directory PLOT/TEST4:

cross.plt: shows three sections of the hydraulic conductivity in the model area;

crflow.plt: shows the simulated flow arrows in the three sections in the groundwater zone;

Results can also be retrieved as ascii files (tables) of e.g. the simulated groundwater flow in the x-direction some days after start of the simulation. This is done by loading the specification file QCtest4.or located on the directory MACRO.

QCtest5

The setup QCtest5 is a combination of QCtest1 extended with the inhomogeneities (lenses) and QCtest3 i.e. the setup includes the components for groundwater flow, overland and channel flow and exchange flows between river and groundwater.

The setup can be inspected by loading the QCtest5.fsf file and going through the following menus:

F.1.1 - catchment definition;
F.1.2 - the geological interpretation;
F.1.2a+b - the geological layer and its hydrogeological parameters;
F.1.3a+b - the geological lenses and their hydrogeological parameters;
F.1.3 - the vertical discretisation which in this case follows the geological layer;
F.1.4 - the initial conditions which correspond to a simulated potential head;
F.1.5 - the boundary conditions which is a no-flow condition along the entire boundary;
F.1.6 - the parameters for drainage i.e. drain level and time constant;
F.1.10 - the river network;
F.1.11 - parameters for the overland and river flow;
F.1.15 - definition of data for the 'dummy' component;

The QCtest5.fif input data file is generated as described above.

The QCtest5.fif input data file can be inspected using MSHE.IR from menu U.2. You can e.g. see the distribution of the vertical hydraulic conductivity by loading and executing the specification file QCtest5.ir from the MACRO directory.

The simulation can be started from menu F.4.

Try after the simulation to create other plots.

The water balance in the catchment can be investigated from menu U.8 by loading and executing the specification file QCtest5.wbl.

Qctest6

The model setup QCtest6 includes the all the components in MIKE SHE WM, i.e. it is a combination of the previous setups. A limited preliminary calibration has been carried out - try to calibrate the setup to the measured river flows!. The setup can be investigated by loading the QCtest6.fsf file and going through the following menus:

F.1.1 - catchment definition;
F.1.2 - the geological interpretation;
F.1.2a+b - the geological layer and its hydrogeological parameters;
F.1.3a+b - the geological lenses and their hydrogeological parameters;
F.1.3 - the vertical discretisation which in this case follows the geological layer;
F.1.4 - the initial conditions which correspond to a simulated potential head;
F.1.5 - the boundary conditions which is a no-flow condition along the entire boundary;
F.1.6 - the parameters for drainage i.e. drain level and time constant;
F.1.7 - the vertical distribution in the soil profiles;
F.1.8 - the classification of the unsaturated zone codes and the spatial distribution of the soils;
F.1.10 - the river network;
F.1.11 - parameters for the overland and river flow;
F.1.12 - the distribution in time and space of parameters for the evapotranspiration calculations (potential evaporation, vegetation, leaf area index, root distribution and empirical parameters for the Kristensen and Jensen evaporation model;
F.1.14 - the parameters for the snow melt routine;

The QCtest6.fif input data file is generated as described above. The simulation time is much larger in this setup and the simulation will therefore take some time.

The QCtest6.fif input file can as usual be inspected with the input retrieval programme MSHE.IR from menu U.2 - try now to define your own specifications!

There is only one specification file for graphical presentation of simulated and measured river flow located on the directory PLOT/TEST6. Try after the simulation to create your own plots!

Model Verification Examples

Abstraction under confined conditions (Theis)

Theis formulated a theoretical solution for abstraction in a two-dimensional homogenous and isotropic aquifer of infinite areal extent. The flow setup file is called theis.fsf and is located under <data\examples\verification>

The governing differential equation is

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (1)$$

The boundary conditions are

$$r\frac{\partial h}{\partial r}_{r=r_b} = \frac{q_{out}}{2\pi T} \qquad (2)$$

$$h(r) = h_0 \; for \; r \to \infty$$

and the initial conditions

$$h(r) = h_0 \qquad (3)$$

where

h - head [m]
h_0 - initial head [m]
T - transmissivity [m^2/day]
S - storage coefficient [-]
t - time [days]
r - distance from centre of island [m]
r_b - radius of well [m]
q_{out} - abstraction [m^3/day]

The theoretical solution for the drawdown is given by

$$s = \frac{q_{out}}{4\pi T} w(u) \qquad (4)$$

where

$$w(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + ... \qquad (5)$$

$$u = \frac{r^2 S}{4Tt}$$

Setup parameters

T= 1116 m^2/day
S= 1.003e-2
h_0= 70 m
$q_{out,11,11}$= 4546 m^3/day
Lx= 10000 m
Ly= 10000 m
Nx= 21
Ny= 21

Simulation parameters

Δt= 1 day
iteration stop criteria= {1e-3 m}
simulation period= 60 days

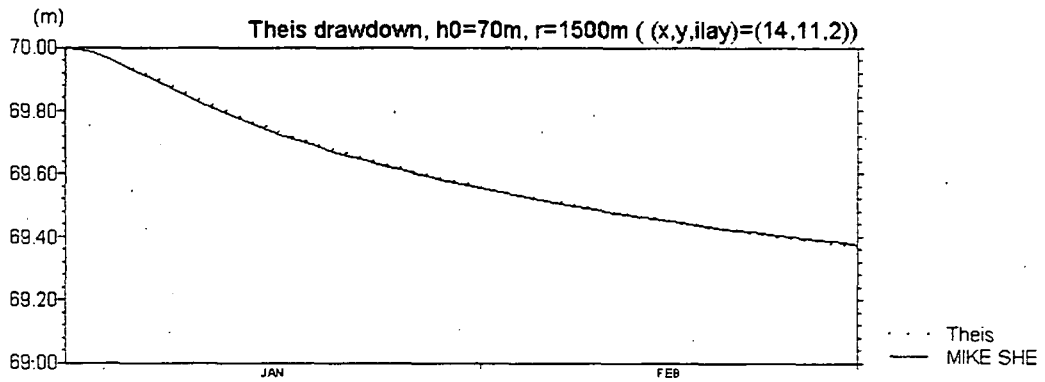

Figure B-1 Computed Theis drawdown by MIKE SHE compared by the theoretical solution.

Abstraction under unconfined conditions in an island

This test consider the drawdown in a island due to abstraction. See Figure B-2. The flow setup file is called island.fsf and is located under <data\examples\verification>

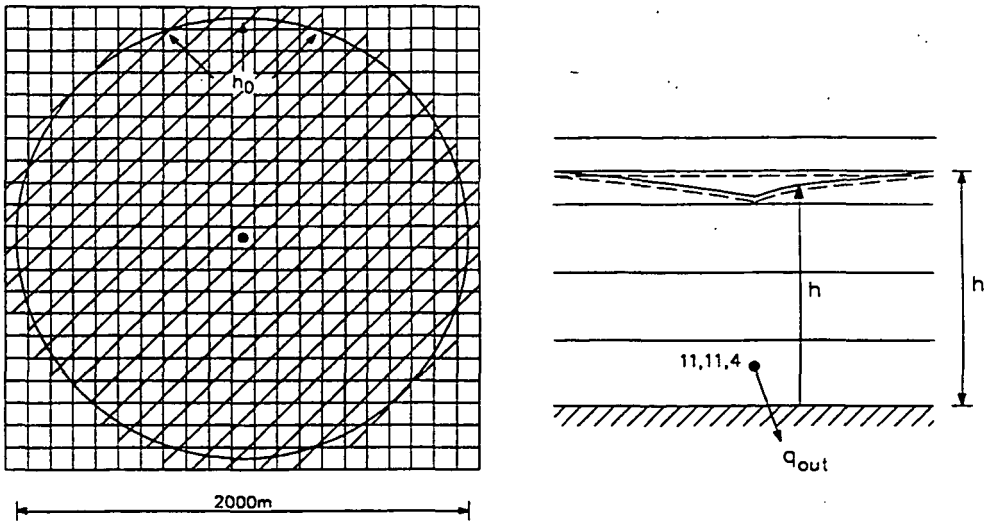

Figure B-2 Horizontal and vertical discretisation.

When neglecting the vertical pressure gradient (Dupuit-Forchheimer approximation) the theoretical solution is given as

$$h(r) = \sqrt{\left(-\frac{q_{out}}{\pi K}\ln\frac{R}{r} + h_0^2\right)} \qquad (6)$$

where

q_{out} - abstraction
R - radius of the island
h_0 - initial head
K - hydraulic conductivity
r - distance from centre of island

Equation (6) describes a steady-state solution. The steady solution is found either by choosing a simulation period over which the solution reaches a steady-state or by letting the storage and specific yield coefficient be zero (for the PCG-solver only).

Setup parameters

K = 43.2 m/day
S_{art} = {0.0002}
S_{free} = {0.2}
h_0 = 70 m
$q_{out,11,11}$ = 13700 m^3/day
Lx = 1000 m

Ly = 1000 m
Nx = 21
Ny = 21
Nlay = 4

Simulation parameters

Δt= 1 day
iteration stop criteria= 1e-3 m
simulation period= 70 days

Figure B-3 shows the head as a function of *r* predicted MIKE SHE compared to an analytical solution.

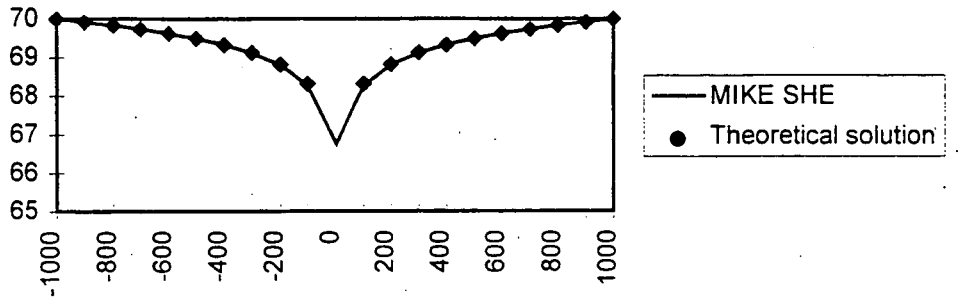

Figure B-3 Head as a function of r

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Instantaneous material release from horizontal line-source

This test consider solute transport in a stationary flow field. The flow setup file is called ad3dtest.fsf and the transport setup file is called ad3dtest.tsf . Both files is located under <data\examples\verification>

Model setup

The modelled area is a rectangular body ($0 \le x \le 20, -10 \le y \le 10, 0 \le z \le 5$) (see Figure B-4); length of the line source is b=10 m, its central point is the point (9.5,0,4.5). The line source releases instantaneously 1 kg/m of material. The distribution of the interstitial velocities in the area is permanent and homogeneous, as described below

u_x = 0.04m/d
u_y = 0.0m/d
u_z = 0.0m/d

i.e. the water movement is parallel to the x-axis

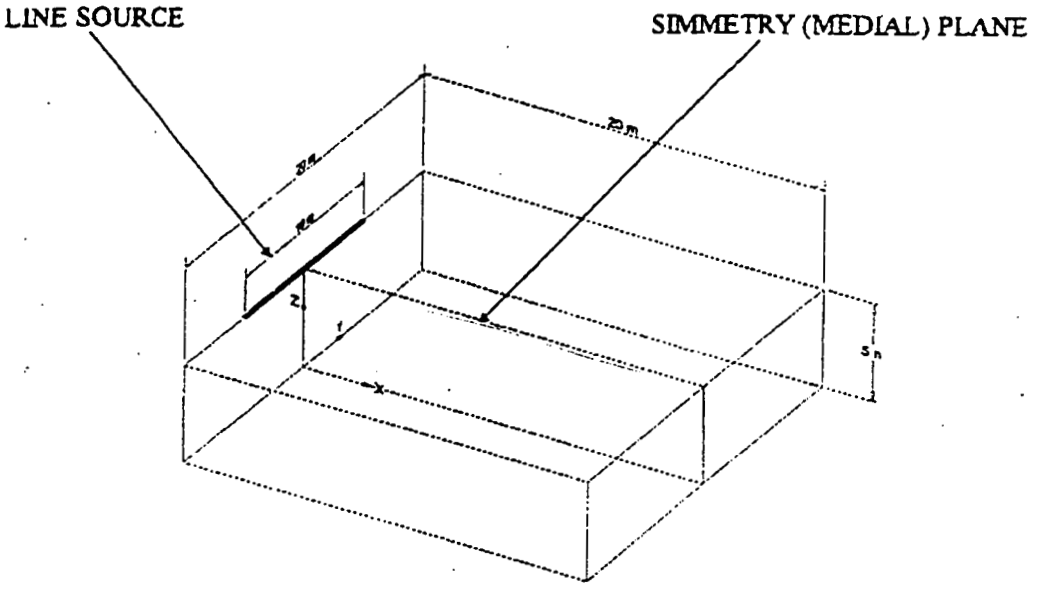

Figure B-4 Model geometry

The boundary conditions are:

$$\vec{n}(\vec{u}c - D\nabla c) = q_c \qquad (7)$$

$$q_c = \begin{cases} 1\,kg/s, if \le 1s \\ 0 \;\; otherwise \end{cases} \qquad (8)$$

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in the points of the line source (x=9.5,-10≤y≤10,z=4.5), where $\vec{u}$ is the vector of interstitial velocities, $\vec{n}$ is the normal vector of the surface, D is the hydrodynamic dispersion tensor; and

$$\vec{n}(D\nabla c) = 0 \qquad (9)$$

for all other boundary surfaces.

Initial conditions:

$$c(x, y, z, 0) = 0 \qquad (10)$$

for all points.

The model parameters are summarised in Table 6-1

Table 6-1 Test parameters

Parameters		**Value**	**Unit**
effective porosity	n_e	0.1	-
retardation factor	R_d	1.0	-
interstitial velocity	u	0.04	m/d
longitudinal dispersivity	α_L	1.0	m
transversal dispersivity	α_T	0.5	m
x dispersion coefficient	D_x	0.04	m^2/d
y dispersion coefficient	D_y	0.02	m^2/d
z dispersion coefficient	D_z	0.02	m^2/d
layer thickness	h	5.0	m
decay constant	λ	0.0	1/d
length of line source	b	10.0	m

The area is discretized to uniform cube elements of 1m x 1m x 1m. The line source is represented as a initial concentration in 10 cells (i=11,7≤j≤17,lay=1)

Theoretical solution

The 3D transport equation:

$$\frac{\partial c}{\partial t} + \frac{u}{R}\frac{\partial c}{\partial x} = \frac{D_x}{R}\frac{\partial^2 c}{\partial x^2} + \frac{D_y}{R}\frac{\partial^2 c}{\partial y^2} + \frac{D_z}{R}\frac{\partial^2 c}{\partial z^2} - \lambda c \qquad (11)$$

$D_x = \alpha_L u$ [L^2T^{-1}]
$D_y = \alpha_T u$ [L^2T^{-1}]
$D_z = \alpha_T u$ [L^2T^{-1}]
α_L = longitudinal dispersivity [L]
α_T = transversal dispersivity [L]

The initial and boundary conditions:

$c=0$ if $t=0$

$c=0$ $x=\infty, y=\infty$

$\frac{\partial c}{\partial z}=0$ $z=0, h=0$

where h is the layer thickness.

The solution of equation 6-5 in case of line source of length b, the central point of which is $P(0,0,z_0)$

$$c(x,y,z,t)=\frac{1}{n_e R}X(x,t)Y(y,t)Z(z,t) \tag{12}$$

where

$c(x,y,z,t)$ = concentrations due to unit pollutant load [M L^3]

$$X(x,t)=\frac{1}{\sqrt{4\pi D_x \frac{t}{R}}}\exp\left[-\frac{\left(x-\frac{ut}{R}\right)^2}{4D_x\frac{t}{R}}-\lambda t\right] \tag{13}$$

$$Y(y,t)=\frac{1}{2b}\left[erf\left(\frac{\frac{b}{2}+y}{\sqrt{4D_y\frac{t}{R}}}\right)+erf\left(\frac{\frac{b}{2}-y}{\sqrt{4D_y\frac{t}{R}}}\right)\right] \tag{14}$$

$$Z(z,t)=\frac{1}{h}\left[1+2\sum_{m=1}^{\infty}\exp\left(-\frac{m^2\pi^2 D_z t}{h^2 R}\right)\cos\left(m\pi\frac{z_0}{h}\right)\cos\left(m\pi\frac{z}{h}\right)\right] \tag{15}$$

Equation 6-6 is valid for a horizontally infinite aquifer of thickness h

Results

Figure B-5 and Figure B-6 shows the break- through curves for selected cells in the model area.

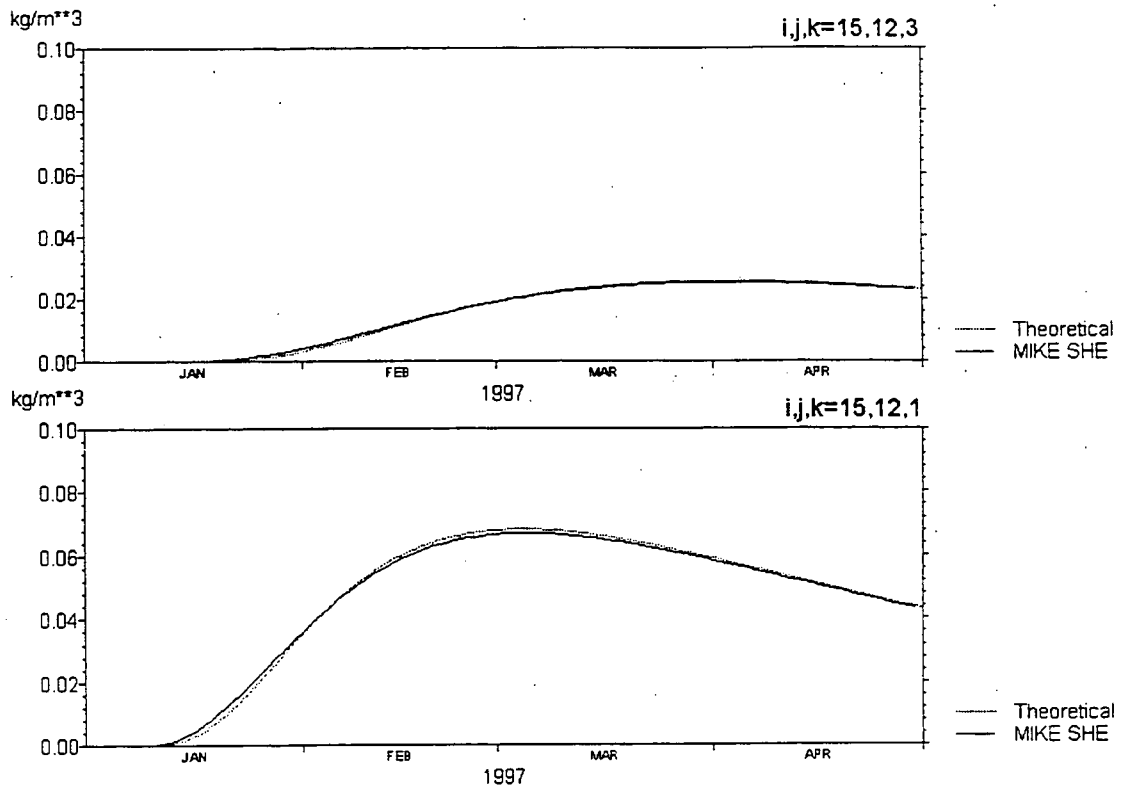

Figure B-5 Break-through curve for cell (i,j,lay)=(15,12,3) and cell (i,j,lay)=(15,12,1)

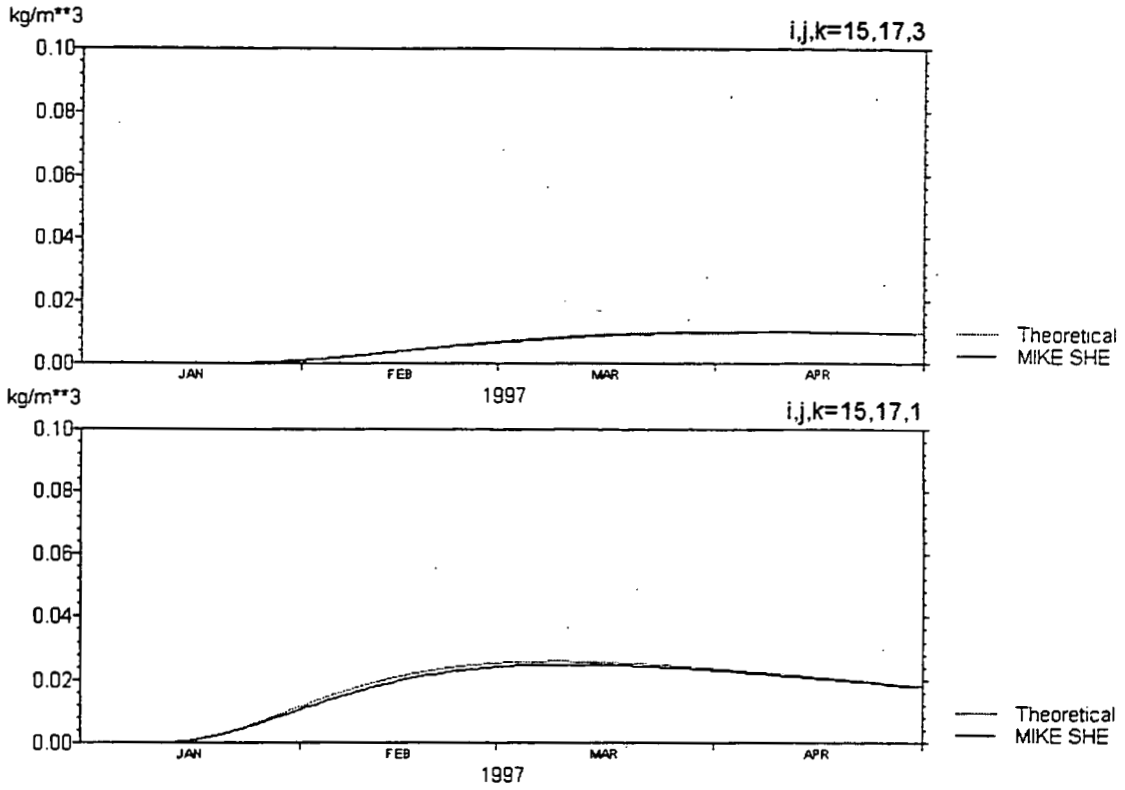

Figure B-6 Break-through curve for cell (i,j,lay)=(15,17,3) and cell (i,j,lay)=(15,17,1)

Appendix C

MIKE SHE MP

User Guide and Technical Reference

Macropore Flow in the Unsaturated Zone

Preferential flow or macropore flow, which can be important in many soil types (< biblio >), is optionally incorporated in addition to the Richards' type flow in the MIKE SHE WM. The physically based description of macropore flow assumes a secondary pore domain through which water is routed separately, but with exchange with the surrounding bulk porosity (or matrix porosity) being possible. MIKE SHE MP is still not implemented in MIKE SHE's graphical user interface. Thus required input data are specified in an extra ASCII file.

Activating MIKE SHE MP:

Before starting MIKE SHE the environment variable <macropore> should be ON, and an extra ascii-input file named WMsetupname.mpd is required in the directory containing the fsf-setup files. This file should contain the following extra parameters:

Ascii-print control parameters:

printmp: Logical parameter (t/f). If printmp = t simulation results in the gridpoint (ixmpout,iympout) are stored as ascii-files. This may ease testing and calibration of single soil columns.

ixmpout: x-coordinate of uz-column for which ascii-printout of macropore results are stored.

iympout: y-coordinate of uz-column for which ascii-printout of macropore results are stored.

Iteration control parameters

thresh: Iteration stop criteria in the macropore solution scheme defined as a fraction of macroporosity at ground level. Recommended value is $1x10^{-5}$

omega: Ω, weighting factor ($\Omega \in [0,1]$) used in updating macropore water contents between iterations. Recommended value is 0.6.

idiv: Number of extra time steps per time step reduction. Recommended value is 10.

maxmodiv: Maximum allowable number of time step reductions. Recommended value is 10.

itmo: Maximum allowable number of iterations in the macropore solution scheme.

For each unsaturated soil profile defined in the fsf-file:

$e_{ma,\theta}$ (emazero) - Macroporosity at ground surface.

b_0 (bzero) - Constant, defining the degree of depth change in macroporosity (eq.1).

$K_{s,ma,\theta}$ (cmas) - Saturated hydraulic conductivity of the macropores at ground surface (m/s)

n^* (nstar) - Exponent in the hydraulic conductivity function for the macropores (eq. 6).

β_{mp} (betamp) -Water transfer coefficient (m^{-2}) accounting for water exchange between matrix and macropores (eq. 5). Expected to vary from 0 to 200. Larger values diminishes the hydraulic bypass effect of the macropores.

For each soil type defined in the UZ-database:

soil type: is the number of the soil type in the UZ data base. This number is internal in the program and cannot be seen in the UZ data base. However, the numbering follows the order of definition in the soil data base.

ψ_p: Matrix threshold pressure (m) at which macropore flow is initiated. This parameter may be distributed in depth. The value may be below zero as e.g. the air entry point on the retention curve.

Example of fsfname.mpd:

```
FILETYPE DATATYPE VERNO:   1111        0       524
printmp ixmpout iympout
   t        2       2
thresh   omega   idiv   maxmodiv   itno
1E-05     0.6     10       10        50
number of profiles
1
profile number        cmas    nstar   betamp   emazero   bzero
            1        E-04      5       20.      0.02      1.0
number of soil types
3
soil type      matrix-MP exchange threshold pressure
1               -0.15
2               -0.15
3               -0.15
```


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Definition of macroporosity

Macropores are defined as a secondary, additional pore domain in the unsaturated zone. The macropores are assumed to be continuous and extend fully from the ground surface through the unsaturated zone. An exponential decrease (or increase) in the macroporosity e_{ma} with depth is accounted for:

$$e_{ma} = e_{ma,\theta} \exp\left(-b_0 z\right) \quad (1)$$

where $e_{ma,\theta}$ is the volumetric macroporosity at the ground surface, z is depth and b_0 is a constant, defining the degree of depth change.

Retention characteristics of macropores

A soil moisture retention curve is not defined for the macropore flow domain because any capillary effects in the macropores are neglected. However, as macropore flow may occur under non-saturated conditions it is possible to define a " threshold matrix pressure" (ψ_t) for the soil matrix at which macropore flow will be initiated. In this way the pressure potential in the macropores may become negative.

Water flow

Water flow in the macropores is assumed to be laminar and not influenced by capillarity. The vertical volumetric flux (positive upwards) is then obtained from the reduced Darcy's law:

$$q_{ma} = - K_{ma}(\theta_{ma}) \quad (2)$$

where $K_{ma}(\theta_{ma})$ is the hydraulic conductivity of the macropores. The continuity equation is expressed as:

$$\frac{\partial \theta_{ma}}{\partial t} = - \frac{\partial q_{ma}}{\partial z} - S_{ma} \quad (3)$$

where θ_{ma} is the volumetric soil moisture in the macropores and S_{ma} is a sink term for water exchange with the surrounding matrix. Combining Equations (2) and (3) yields the governing equation for the macropores:

$$\frac{\partial \theta_{ma}}{\partial t} = \frac{\partial \left(K_{ma}(\theta_{ma})\right)}{\partial z} - S_{ma} \quad (4)$$

When the macropore option is used the term S_{ma} becomes a source/sink term in Richards' equation. This term is given by

$$S_{ma} = \beta_{mp} K(\theta)\left(\psi_{ma} - \psi_{mi}\right) \quad (5)$$

where ψ_{ma} and ψ_{mi} are the water pressure in the macropores and in the matrix, respectively ($\psi_{ma} \geq \psi_t$) and $K(\theta)$ is the hydraulic conductivity in the matrix. β_{mp} is an empirical first-order linear water transfer coefficient, which is expected to increase with decreasing distance between macropores and with increasing macropore surface area and tortuosity.

Hydraulic conductivity in macropores

In the macropores a simple power law function is assumed to represent the conductivity relation:

$$K_{ma}(\theta_{ma}) = K_{s,ma}\left(\frac{\theta_{ma}}{e_{ma}}\right)^{n^*} \quad (6)$$

where $K_{s,ma}$ is the saturated hydraulic conductivity of the macropores, e_{ma} is the macroporosity, and n^* is an empirical exponent accounting for size distribution, tortuosity, and continuity of the macropores. n^* may vary from two to six, according to *Jarvis* (1991). The lower values represent soils of coarse structure with macropore networks of narrow pore size distribution and little tortuosity, whereas the higher values apply to soils with a wider macropore size distribution and larger tortuosity.

If the macropore option is used the hydraulic conductivity of the bulk soil should exclude the effect of macropores.

The saturated hydraulic conductivity of the macropores $K_{s,ma}$ is assumed to be proportional to the macroporosity:

$$K_{s,ma} = C_k \, e_{ma} \quad (7)$$

where C_k is the proportionality factor. This relation reflects the Poiseuille's law for gravitational full flow in vertical, cylindrical tubes or vertical planar fractures where the linear, vertical flux rate is proportional to the tube diameter or the fracture width.

Defining a saturated hydraulic conductivity at the ground surface $K_{s,ma,\theta}$ yield a distribution function for $K_{s,ma}$ with depth:

$$K_{s,ma} = K_{s,ma,\theta} \exp\left(-b_0 z\right) \quad (8)$$

The actual size, form and number of macropores are not explicitly considered, however. Instead macropore characteristics appear indirectly from b_0, n^* and β_{mp} as n^* is used to describe the hydraulic conductivity as a function of macropore saturation, and β_{mp} is used to describe the exchange of water between the macropores and the matrix.

Evapotranspiration from macropores

Root water uptake and soil evaporation do not take place from the macropore domain.

Boundary conditions

If macropores are included in the simulation the infiltration process includes water entering into the macropores as well as into the bulk soil at the soil surface. In this case water is not ponded on the ground surface until the infiltration capacity of both pore regions is exceeded. Water flow into the macropores commences as the matrix infiltration is surpassed. This condition is calculated and checked similarly to the case without macropores.

The bottom boundary condition for flow in the macropores is a vertical flux at a unit hydraulic gradient. This flux is input to the saturated zone. A coupling of the saturated zone and the unsaturated zone is necessary when the groundwater level passes a computational node. During groundwater rise the water present in the macropores in the bottom UZ layer is released instantaneously to the groundwater, and during groundwater decline the macropores are exposed as empty.